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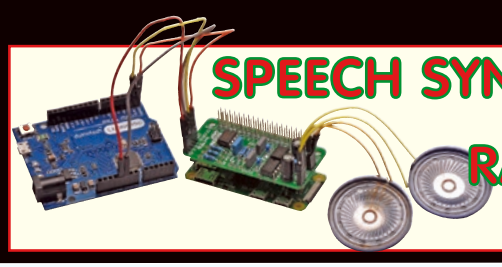

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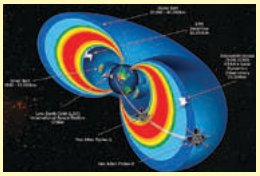

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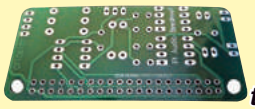

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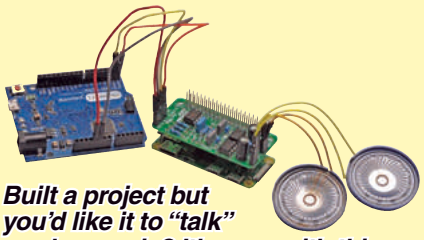

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Editorial Viewpoint

New motor vehicles should have built-in dashcams

After being at the receiving end of several unprovoked "road rage" incidents, I decided to fit front and rear dashcams to all my family's vehicles. The strange part about this is that all these vehicles have reversing cameras, and some even have 360° cameras to help with parking, yet there is no obvious way to record the images from those cameras.

Admittedly, those cameras are designed more for showing images of what's immediately surrounding the vehicle rather than traffic at large, but they could easily be 'paired up' with wide-angle cameras like those used in dashcams, and wired back to a central recording unit.

This could be in the centre console or glovebox, and have an SD card slot for recording video from those cameras while the ignition is on. And many vehicles already have GPS navigation, so they could easily log your position and speed to that card as well. Even for vehicles that don't have navigation, a GPS module would hardly cost sheep stations to add.

The cameras are quite cheap to manufacture. A decent HD dashcam with GPS and all the required electronics, including video encoding, costs around $100 in a retail shop. OEMs would be paying a fraction of that.

Once you take into account the installation labour, wiring and so on, I would estimate that adding front and rear cameras and the necessary recording hardware would add less than $200 to the cost of a vehicle. Even on the cheapest new cars, that isn't a huge increase, and I for one would gladly pay for the convenience.

It would be a great selling point for manufacturers who start doing this across their range. After all, who wants cameras stuck to their windscreen with wires running to the nearest accessory power point? And if the cameras are integrated into the vehicle, they would have an even clearer view of what's going on around you.

I am aware that Tesla vehicles already do this. While their cameras seem to have been originally intended to enable semi-autonomous driving, they also record video (apparently, whether you want them to or not!). And they have even recently added a "Sentry mode" to record would-be thieves and vandals.

But Tesla is a niche brand. They sold around 1000 vehicles in Australia last year, out of a total of 1,153,000 – ie, about 0.1%. Citroën also offer a built-in dashcam in their C3 model, released in March 2018, although this is a $600 optional extra. Citroën are also a very minor player in the Australian car industry. It's about time that mainstream manufacturers start offering similar features.

It's a sad fact that these days, you need to record what's going on around you to protect yourself while driving. There are just too many incompetent and aggressive drivers around to ignore any more. So when somebody busy updating their Twitter, watching YouTube or doing their best 'Stig' impression damages your car, you'll be able to show that it wasn't your fault.

I have to wonder, with all the technology going into vehicles these days like radar cruise control, autonomous braking, lane keeping, semi-autonomous driving, tyre pressure monitoring, phone integration, infotainment and so on, why such a feature has not already become widely available.

Nicholas Vinen

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Questioning use of LiPo charger IC with LiFePO4 cell

I am questioning the use of an MCP73831 charger IC to charge the $LiFePO_4$ cell in the Solar-powered data repeater design published in the May 2019 issue (siliconchip.com.au/Article/11615). This chip is intended to charge Li-ion and LiPo cells with its output regulated to a maximum of 4.2V.

It is unsuitable for $LiFePO_4$ charging because these cells have a full charge voltage of 3.65V. Under charge, the cell will never rise to the module's cut-off voltage, and the cell will fail due to over-charging.

I have used one of these modules to charge a $LiFePO_4$ cell by inserting a forward-biased silicon diode and a schottky diode between its output and the cell's positive terminal, to drop the charge voltage to something like 3.65V. I have also successfully charged three NiMH cells in series using one of these chips, though I would not recommend either of these schemes.

Also, I think there may be a typo in the last paragraph under "power saving features" (page 49). The quiescent current draw is quoted as 9.4mA. I think this should read 9.4µA considering all the power saving measures in the circuit.

Bob Temple,
Churchill, Vic.

Response: you are not the only person to point this out. We were aware that the MCP73831 is intended for charging LiPo cells and has a charge termination voltage of 4.2V. It is also true that the fully charged voltage of a $LiFePO_4$ cell is usually around 3.65V. However, $LiFePO_4$ cells will not be damaged by being 'over-charged' to 4.2V (although that is the maximum safe voltage).

For example, see the following web page of a battery manufacturer: www.powerstream.com/LLLF.htm

To quote them: "A [lithium ion] battery has a very narrow overcharge tolerance, about 0.1V over the 4.2V per cell charging voltage plateau, which also the upper limit of the charge voltage. Continuous charging over 4.3V would either damage the battery performance, such as cycle life, or result in fire or explosion."

"A $LiFePO_4$ battery has a much wider overcharge tolerance of about 0.7V from its charging voltage plateau of 3.5V per cell. When measured with a differential scanning calorimeter (DSC), the exothermic heat of the chemical reaction with electrolyte after overcharge is only 90J/g for $LiFePO_4$ versus 1600J/g for [lithium ion]."

"A $LiFePO_4$ battery can be safely overcharged to 4.2V per cell, but higher voltages will start to break down the organic electrolytes."

You could add a series diode from the charger IC's output diode to the cell to reduce the charge voltage if you are concerned. The maximum charge current is only 100mA, and once the cell voltage reaches 4.2V, the charger drops its output to 5mA and waits for it to fall to 3.9V before resuming fast charging.

Another option would be to use a 14500 type Li-ion cell, such as Jaycar Cat SB2300 (800mAh), as the MCP73831 designed for this type of cell. But we have more faith in $LiFePO_4$ cells as they have a wider range of voltage tolerance and are far less prone to catching fire.

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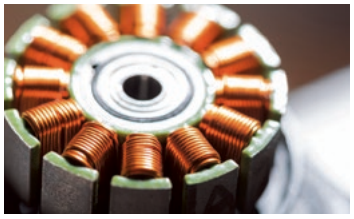

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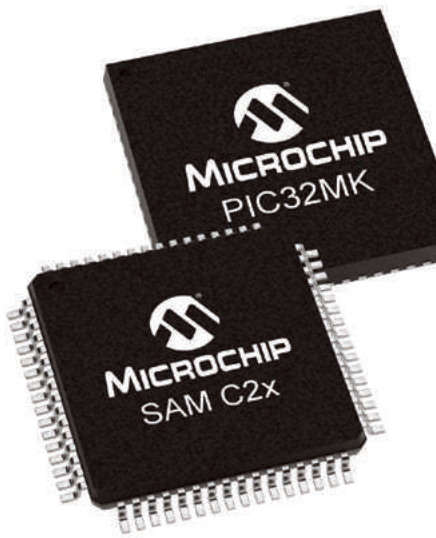

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In retrospect, we probably should have used an MCP73123 charger IC to avoid this concern. It is intended for charging $LiFePO_4$ cells. Unfortunately, it is not pin-compatible with the MCP73831 as it only comes in a DFN package, whereas we used the SOT-23 package IC in our project.

The 9.4mA quiescent current figure is correct. Much of this is consumed by RX1 as it needs to operate continuously, waiting to receive data which is to be repeated.

Comments on UHF Data Repeater

I just finished reading the article in the May issue on the 433MHz Data Repeater. Bravo for its ability to handle a wide range of "device-agnostic" signals. Note that this repeater assumes ASK remote coding; some remotes may well use noise-immune FSK (or better GFSK), and these signals will not be repeated!

Note also that depending on placement, the repeater may blindly repeat other folks' 433MHz signals. It's hard to say whether this would be beneficial or mischievous!

I'm glad you used the $LiFePO_4$ cell, but they only go as high as 3.7V on charge and then settle to a stable 3.2-3.3V. My experiences with these little darlings indicate very high reliability compared with LiPo. Some outdoor equipment of mine is now in its sixth year of continuous operation without any woes.

I've gutted $LiFePO_4$-based solar security lamps for diverse 433MHz projects. Their inbuilt PV panel is usually well-suited to the task, and they're very well sealed for outdoor use. Additionally, folks think they're just a light and don't consider them invasive.

Also, I consider the Jaycar Cat ZW3102 receiver module a much better and more versatile receiver than the other one you've specified. This may be important when signal levels are marginal.

It may be worth rustling up a 433MHz sniffer/direction finder to help constructors when "up a pole" siting the repeater. Check out my instructions on building one at: siliconchip.com.au/link/aaqm

Stan Swan,
Wellington, NZ.

Response: see the letter above regarding $LiFePO_4$ charge voltages. The idea of hiding a wireless transmitter or transceiver inside a solar security lamp is a stroke of genius.

We published a simple sniffer design from Stan in the January 2011 issue, which shows received signal strength using LED brightness (siliconchip.com.au/Article/870).

Report on Israeli lunar lander "Beresheet"

In the November 2018 issue of SILICON CHIP, I wrote an article on the Beresheet lunar lander (siliconchip.com.au/Article/11296).

This was to be Israel's first lunar landing, and only the fourth country to attempt a soft landing on the moon after the Soviet Union, the United States and China. The project was also mostly privately funded.

On April 11th 2019, Beresheet unfortunately crashed during its attempted landing.

A full investigation as to the causes is still to be completed, but there is a suggestion that it was a failure of the inertial measurement unit (IMU), which is thought to have failed during the braking procedure from lunar orbit in preparation for landing.

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While that's a reasonable theory, the official cause will be established (if it can be determined) by a full engineering inquiry now underway.

The reason that the IMU is under suspicion is that it was stated by controllers that during the descent the IMU "is not OK". Then there was a telemetry drop-out, for unknown reasons, then a return of telemetry with more drop-outs following.

After the apparent failure of the IMU and failure to decelerate for landing, a decision was made to do a full computer system reset.

However, by that point, there was not enough time for the computer to reboot; the spacecraft was too low and travelling too fast to slow down in time to avoid crashing, even if the reboot had been successful.

The final telemetry reading received was with the spacecraft at an altitude of 149m, descending at 134m/s (482km/h) and with a ground (horizontal) speed of 947m/s (3409km/h).

Despite the failure to perform a soft landing, the XPRIZE Foundation still awarded US$1 million to SpaceIL for a "successful entry into lunar orbit and for its attempt to land on the lunar surface – both of which are 'firsts' for a privately-funded entity, marking a new era in space exploration".

On April 13th, there was an announcement by billionaire Morris Kahn (the main funder for Beresheet) that there would be a second landing attempt called Beresheet 2. This mission is expected to carry more scientific instruments and be completed within two years.

Full telemetry data was published during the live stream of the event which can be seen in the video titled "LIVE broadcast - Beresheet lands on the Moon Fasten your seatbelts, we are about to land." at: https://youtu.be/HMdUcchBYRA

There is also a very good video with annotation titled "How Israel's Lander Crashed Into The Moon, And How Falcon Heavy Flew" at: https://youtu.be/uH9aX5evxqU

Dr David Maddison,
Toorak, Vic.

Replacement washing machine controller wanted

I live in Darwin and we have one of the highest incidences of lightning strikes in the world.

Consequently, I currently have a stockpile of washing machines with blown control boards sitting in my workshop. Manufacturers really know how to charge for replacement parts. They often ask for more than the machine is worth!

Would it be possible to use an Arduino or similar and write a generic program to replace the manufacturer-specific control board?

The inputs and outputs are simple as there is only water level switch, water solenoids, pump and motor. The touchscreen could fit over the existing controls.

Lloyd English,
Darwin, NT.

Response: We have considered doing something similar in the past, but in the end, it was easier to fix the failed board than design a new one from scratch. It would be tough to design

one to suit all the different machines in use today (or even a majority of them).

Motor types vary between manufacturers, with some direct drive, some belt drive etc. The original wash cycles and such would be virtually impossible to duplicate.

We think that if you are at such risk, it is better to run the washing machine via a large isolation transformer, which would provide some protection from lightning damage. But the only sure way to protect the machine from damage is to unplug it when not in use.

Adding snooze function to DAB+/FM/AM Radio

I just finished building the DAB+/FM/AM Receiver (January-March 2019; siliconchip.com.au/Series/330). At the end of the last article, you suggested submitting useful enhancements. For me, not only being able to complete the project but to also modify/add to the code to include a functioning snooze option was a buzz.

I have included a photo of the final unit (shown at right) with various attachments. I had a great time completing the project.

Martin Caro,
Orange, NSW.

Adding Bluetooth support to Wide-range LC Meter

I'm very pleased with your LC Meter project from the June 2018 issue (siliconchip.com.au/Article/11099). I built it intending to add remote connectivity, so I opted for a Bluno Bluetooth low-energy (BLE) board instead of the specified Arduino Uno.

I then developed an Android phone app to receive and display the measurement data in a similar fashion to the onboard LCD screen in your original project.

I added some dynamic colour coding to the app display and speech synthesis to the measurement displayed on the fourth line (shown at right), so it could be a baseline for all sorts of useful embellishments.

Keep up the good work.

Steve Ereaut,
Scullin, ACT.

Portable DAB+/FM/AM Radio wanted

I am very interested in building your DAB+/FM/AM Tuner (January-March 2019; siliconchip.com.au/Series/330). Will it have the option of being fully portable as a standalone radio receiver?

I want to be able to just install a few off the shelf batteries to make it truly portable and convenient. Also, it would be great if it had at least one internally-mounted speaker, like other portable radios. Your design doesn't seem to include an internally mounted speaker, nor does it seem to be battery-powered.

Yes, I know I could plug in my own battery pack and even make my own external speaker to connect to this unit. But then I would have to carry around all these separate units, and it would make it not worth the hassle of taking the unit anywhere.

Maybe there could be an option of a larger custom-made case that has a battery compartment and also an internal mounted speaker to make the unit a portable take anywhere radio.

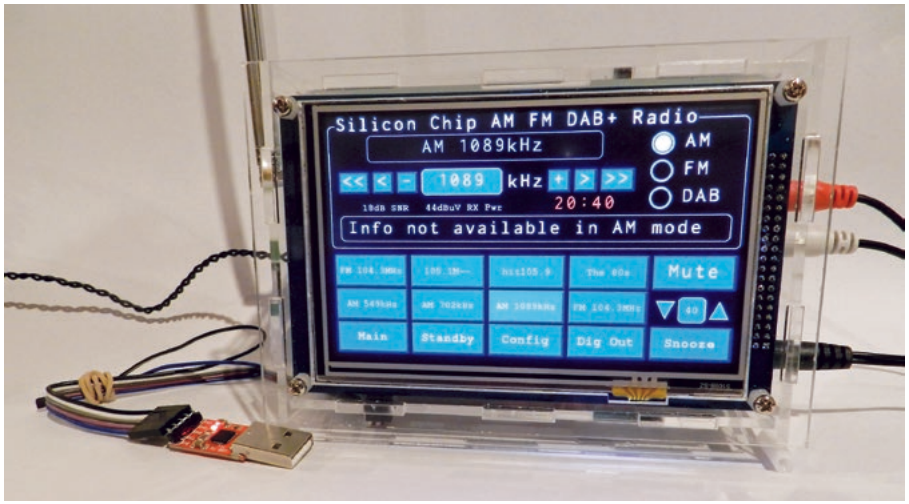
Jaycar sells a radio that has DAB+/FM/AM and even shortwave frequencies all-in-one unit, Cat AR1946. But I would like to build my own to ensure it has very good sound quality.

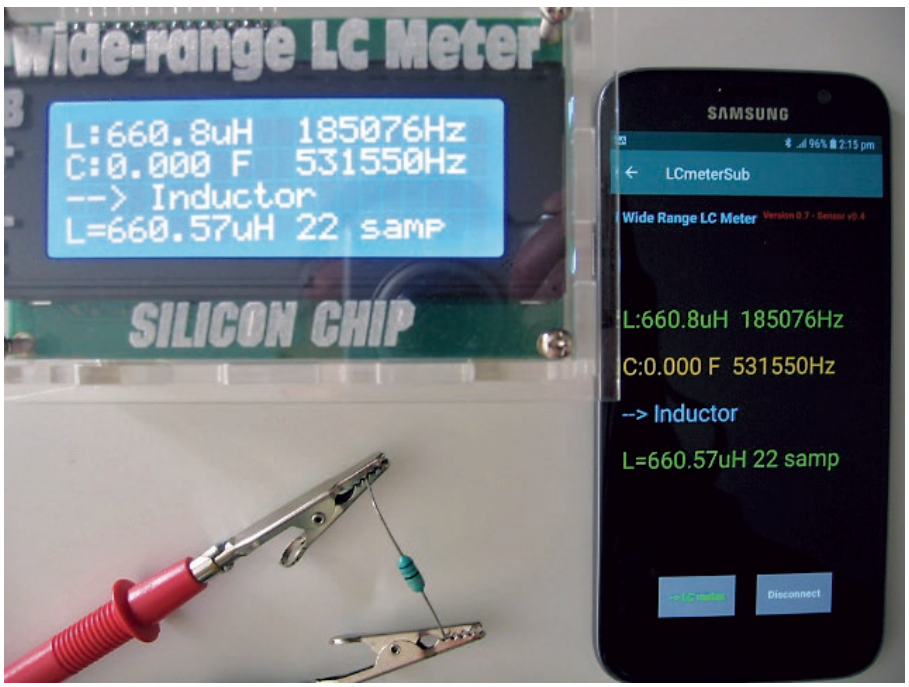
All the best to you. SILICON CHIP is a great magazine!

Kosmas Papandoniou,
Ivanhoe, Vic.

Response: We felt that this project was already vast and complex without adding a battery, charger and so on. As you suggest, these are things that would not be difficult for constructors to add.

You would need to build the radio into a larger case, with enough room for a battery and speaker(s). You could then fit an internal Li-ion/LiPo/LiFEPO_4 battery pack and charger module. Hopefully, there is an off-the-





shelf case available that has suitable dimensions.

We will consider publishing a follow-up article describing how to make the radio portable. Our testing included running it off a USB battery bank with no changes to any of the electronics and it worked fine and sounded great, but we were using external speakers.

Imported products may have fake CE labels

I am currently in a legal dispute with a local (New Zealand) supplier of defective water pumps. I bought a pump from them in late 2017. It worked well for almost a year, but in late October 2018, the water delivery began pulsating. Over time, this became worse. Clearly, something was seriously wrong with the pump.

When I took a close look at the pump, I noticed a suspicious rust-coloured drip-line emerging from the bell housing, which made me think that the pressure tank had rusted through. A domestic water pump should give at least 10 years of service; serious rust developing in less than a year is in no way acceptable.

But that was just the start of the problems that were to ensue. As the pressure pulsations became progressively worse, it began to emit a metallic graunching noise. The obvious conclusion was that the brass impeller had suffered fracture/separation from the motor shaft and was 'snatching' on the spinning motor shaft, hence the pressure pulsations.

As if this wasn't enough, while removing this heap of junk for an inspection, the pressure switch fell off in my hand! There were indications of yet more corrosion. There was something fundamentally wrong here.

One of the primary factors that convinced me to buy this product was that it was extensively marked on both outer packaging and pump casing with the renowned "CE" (Conformite European) standards compliance symbol, recognised as one of the world's most demanding set of quality standards.

How could this be? Surely, a product marked with the prestigious "CE" symbol shouldn't have this many problems!

The conclusion became obvious. The instruction manual contained no declaration of conformity to any EU standard, nor any other for that matter. It became clear to me that all the applied "CE" markings on the pumps I had purchased in good faith were fake, including the markings on the box it came in, and even the holographic sticker on the unit!

Investigating further, I learned that this is an all-too-common scam perpetrated by numerous Chinese manufacturers, who claim that these labels mean "China Export", despite them being virtually identical to the Conformite European logo. Thus, the customer is deceived!

As far as I am concerned, the importation and marketing of this junk are unconscionable and unethical. I believe it is also a legal breach of the Fair Trading Act. I think the importation of equipment with fake compliance labelling should be outlawed.

Andre Rousseau,
Auckland South, NZ.

Surround Sound Decoder works well with SC200 amplifier

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on how to hook up the digital audio output of a television which carries Dolby Digital/DTS digitally encoded surround sound signals to the input of a standard amplifier, such as the one I built based on your SC200 modules.

You pointed me to an item on eBay (www.ebay.com.au/itm//263547481266) which I then purchased and hooked up to my now finished amplifier.

I was astounded by the improved sound quality with the new decoder, compared to the low-cost stereo commercial DAC I had been using previously.

Although I am only using it in stereo mode at the moment, the effect was not just to improve the frequency response: I now notice much greater spatial detail in the sound, perhaps best described as an overall real increase in natural sound reality.

The bass is better defined and has a greater impact, especially notable with very low-frequency sound effects. These comments apply to all sound sources, whether HDMI or optical digital. I have not tried to compare the Dolby decoder on the DVD player against the new unit.

I think this would be a fantastic unit to build into the Tiny Tim amplifier described in the October & December 2013 and January 2014 issues (siliconchip.com.au/Series/131). It should give excellent sound quality, as well as the ability to handle surround sound encoding.

Avoiding leaking batteries

Regarding the question "Why do batteries leak more in modern equipment?" asked by R. B. in the February 2019 issue, I have also had trouble in the past few years with equipment being damaged by leaking alkaline cells.

Because electronic devices can be very costly and are easily destroyed by leaking cells, I do not buy bulk packs of cells any more. I think that these may contain cells which have been sitting around for longer and so are closer to the end of their shelf life compared to those in the smaller packs.

My suggestions are: only use cells from reputable manufacturers; measure battery current flow in devices which are switched off to ensure there is no 'phantom load'; if possible, remove the cells from devices when they are not in use; and use Vaseline on a cotton bud to coat the springs and end contact plates, to try to minimise damage if a cell does leak.

Anthony W. S. Farrell,
Kingscliff, NSW.

Praise for Silicon Chip DAC design

Being of advancing age, I spend a lot of time listening to my considerable collection of CDs (both old and newer). I also watch a few DVDs of the music variety.

Recently I felt the urge to avail myself of the newer Blu-ray technology, so I took myself off to our local electronics store. Imagine my dismay when I discovered that out of the ten or fifteen players on display, not one had analog stereo outputs.

They all had only digital coaxial and/or TOSLINK sockets. I bought one anyway, paying about $170, and ordered a relatively cheap digital-to-analog converter on eBay. The resultant sound was a little less than encouraging, due at least in part, to the fact that it operated from a single 5V DC supply. I believe it was let down by the analog stages following the DAC chip.

Enter the Silicon Chip Stereo Digital Converter (September-November 2009; siliconchip.com.au/Series/4). I managed to buy one of the last kits from Altronics. I understand that once they have sold out of the current stock, they will be discontinued. The kit was straight forward to assemble and thankfully worked first time (phew!).

I can only say that the definition and dynamic range this converter provides is outstanding. It has opened up a whole new dimension that I have not heard before from my CDs, even compared to players with analog outputs I have owned in the past. My hearing is quite good for my age, having been told recently by an audiologist that I have the hearing of a 30-year-old – well under half my actual age!

One other problem with the current crop of players under several hundred dollars is that they don't have a front panel display, or if they do, there is no track number displayed, only the elapsed time for each track. One has to turn the TV on to get that information, which kind of defeats the purpose if you only want to listen to music.

You need a dedicated CD player or a Blu-ray player costing upwards of $1,000 plus to get those features, which were standard on pretty much all CD players just a few years ago.

For the record, the rest of my music

system consists of a NAD 3020A integrated amplifier, Bowers & Wilkins DM10 speakers and a Wharfedale subwoofer. All vintage stuff – like me!

Given the above, it might be a good idea to revisit the 2009 project and come up with an up-to-date design, because of the lack of players with analog outputs available at a reasonable cost.

Congratulations on a great magazine. I have spent many happy hours poring over the contents and building projects over many years since its inception and as far back as *Electronics Australia* and *Electronics Today International*.

Rodney Goodwin,
Tinana, Qld.

Nicholas responds: thanks for your feedback. I agree that our DACs sound a lot better than the analog outputs of many disc players (if they still have them) and pretty much all cheap standalone DACs that you can buy. I still use my prototypes regularly.

I revisited the 2009 design with the Crystal DAC upgrade (February 2012; siliconchip.com.au/Article/768) and CLASSiC DAC (February-May 2013; siliconchip.com.au/Series/63).

While these gave a small improvement in audio quality, I think the original 2009 DAC still sounds fine in comparison. The advantages of the CLASSiC DAC are mainly extra features. But it still doesn't have a proper display as such. I agree that a DAC incorporating a display would be a great project. I hope I can find the time to design one.

Can Class-D amp chips be used to drive motors?

I've often thought of how a pair of Class-D amplifiers, configured in bridge mode with an isolating output transformer, could be used to form a variable speed drive for small AC motors. The input would be from a variable-frequency sinewave oscillator.

Many of these small motors are shaded pole types which may mean that they can only be safely operated over a limited input frequency range before overheating (especially at lower speeds).

Perhaps the solution is to reduce the voltage as the impedance falls, but what consequences does this have on the motor's torque, especially starting torque? What happens at higher frequencies? Or is it just too complicated?

We seem to live in a world in which there are many AC motors used for common items. For example, RC cars which use "brushless DC" motors that are basically permanent magnet three-phase AC motors.

Mark Schijf,
Doncaster East, Vic.

Comment: this is an intriguing idea, but a Class-D amplifier has a lot of extra components and features which aren't needed for driving a motor. But in some cases, a Class-D amplifier chip may be the cheapest way of getting several Mosfets wired up as half-bridges or full-bridges, with integrated drivers in a small package.

Much of the complexity of a Class-D audio amplifier relates to the need for the output waveform to closely follow the input waveform, for low distortion and noise, whereas this is not required for driving a motor. Nor is a filter, really; the motor winding inductance does a good job of converting a PWM waveform to a smoothly varying current.

Shaded-pole motors usually have a low enough power rating that overheating is not likely.

Still, it's good practice to avoid running any induction motor at speeds much lower than it is designed to run at for extended periods without additional cooling.

Suggestion for updated GPS Analog Clock Driver

I am writing about the GPS-Synchronised Analog Clock Driver from February 2017 (siliconchip.com.au/Article/10527) with a suggestion for two optional enhancements that your readers may be interested in.

I am currently with my elderly parents who have two wall-mounted analog clocks which they are unable to reach. As such they need one of my nephews or some other "younger" family member to take down and put back up when the batteries need changing or the time needs to be reset for daylight saving etc.

On thinking of these situations, I was wondering if your Clock Driver could be enhanced to include an optional hand-held remote control unit to perform the clock setup, adjustments etc, as well as the option of using a small 230V AC to 3V DC plugpack which could be plugged into a power point next to the clock.

Paul Myers,
via e-mail

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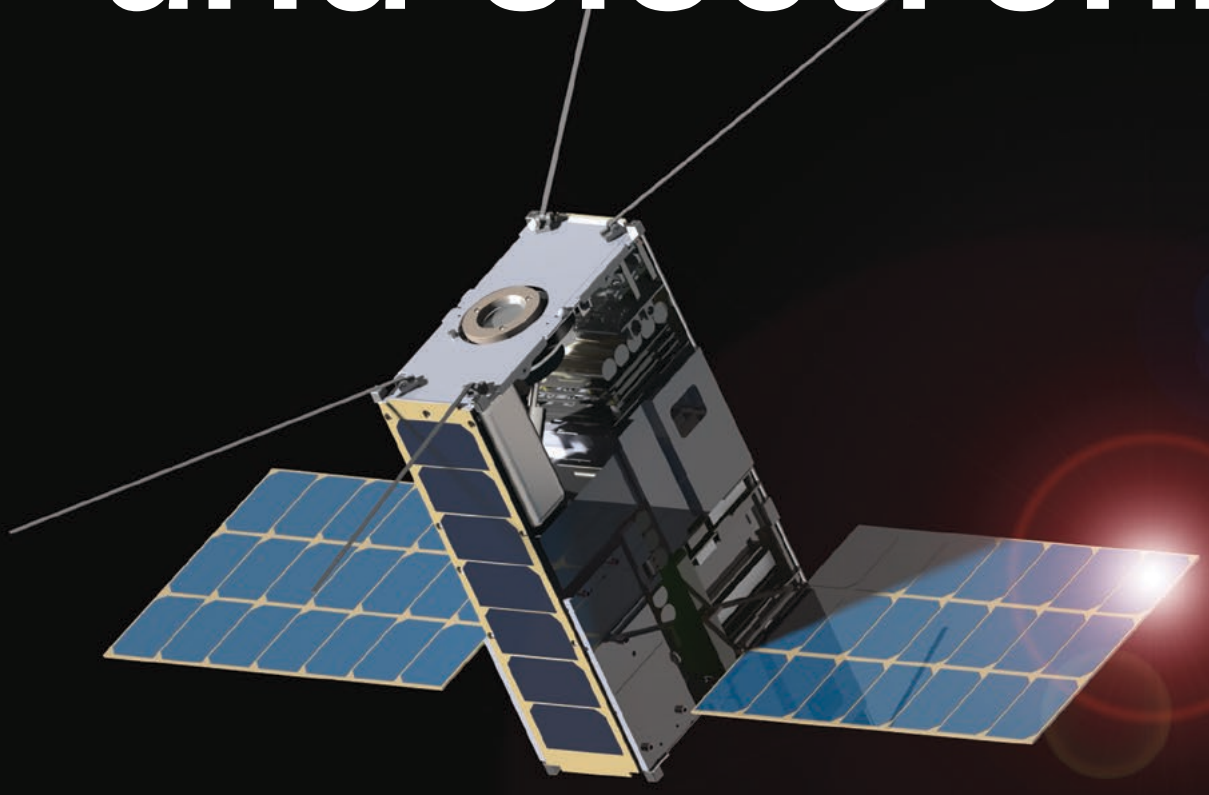
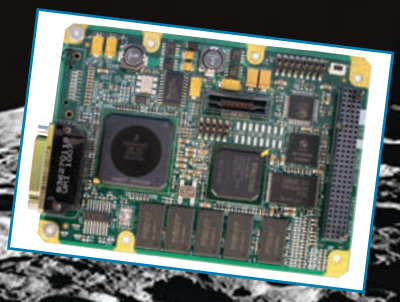
RADIATION and electronics



There are natural and artificial sources of radiation all around us, including nuclear radiation, the solar wind, cosmic rays and electromagnetic pulses. Radiation can have adverse effects on electronics, including critical electronics such as in aircraft, spacecraft and life support systems. It is therefore vital to understand the sources and consequences of radiation events in electronics, and how to prevent radiation from affecting electronics, or manage the results adequately, if that is not possible.

by Dr David Maddison



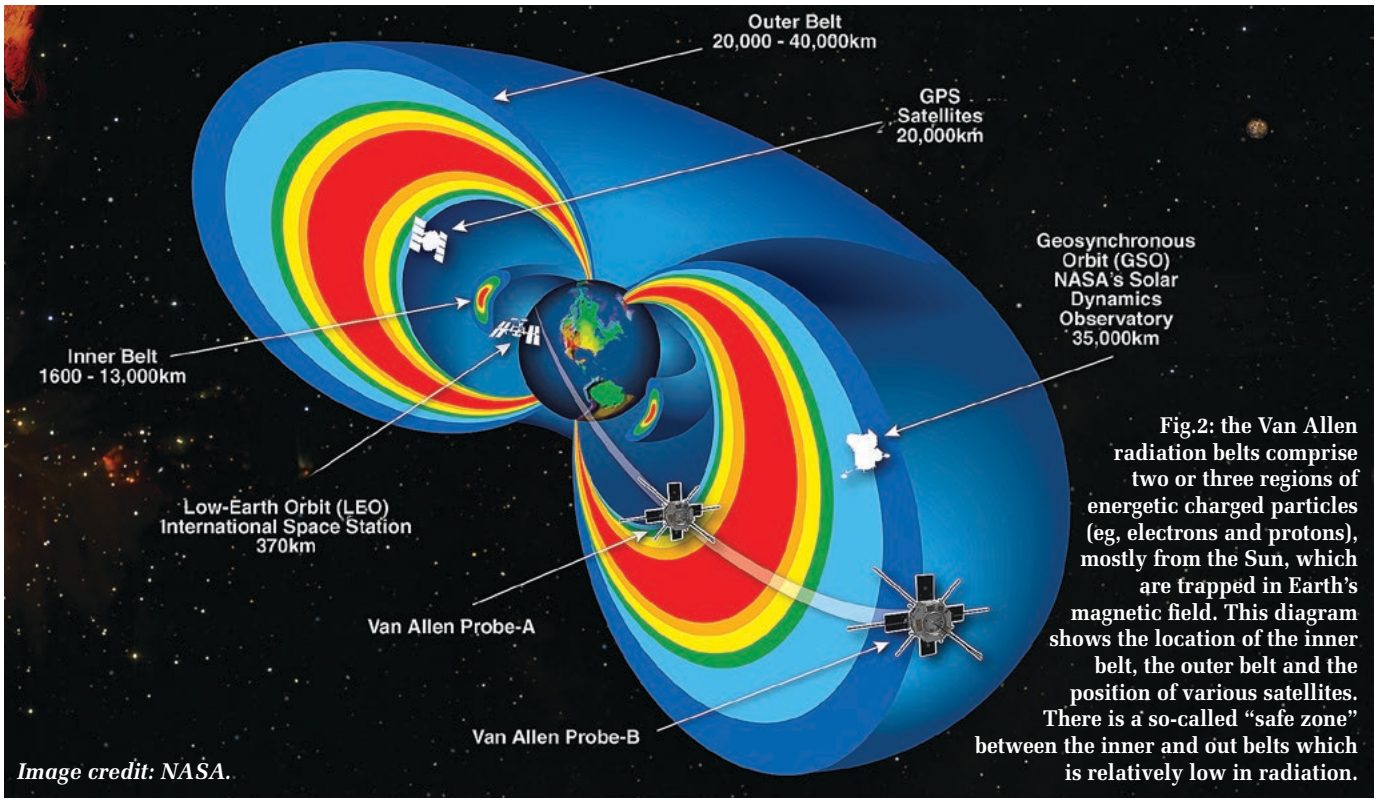


Image credit: NASA.

Fig.2: the Van Allen radiation belts comprise two or three regions of energetic charged particles (eg, electrons and protons), mostly from the Sun, which are trapped in Earth's magnetic field. This diagram shows the location of the inner belt, the outer belt and the position of various satellites. There is a so-called "safe zone" between the inner and out belts which is relatively low in radiation.

Radiation effects on electronics are primarily of concern in aerospace and military applications, although not exclusively so.

Ground-based computers also suffer from radiation-based errors regularly.

This problem has been exacerbated by the continuous reduction in transistor sizes as higher computing speeds and lower manufacturing costs are required; smaller transistors are more susceptible to radiation effects.

Space is one environment where environmental radiation is a major problem for electronics. The types of radiation encountered in space vary enormously with time and locality.

Even if a spacecraft remains within a certain area, eg, the surface of the moon, low earth orbit or geosynchronous orbit, the radiation it is exposed to can vary greatly.

This is influenced by factors such as solar radiation, which varies all the time, and "space weather" in general.

It is not just the intensity or energy of radiation that changes but also the types of radiation particles that are encountered.

And these, in turn, affect both the likelihood and severity of effects on electronic components.

Radiation can cause a variety of impacts to electronics devices, including long term degradation of devices like solar cells, loss or alteration of computer memory contents, halting ("crashing") of computer systems (possibly requiring a reset) or causing computers to issue incorrect instructions.

In severe cases, the entire electronics system or subsystem can burn out, rendering a system permanently inoperative.

Electronics may be irradiated by particles such as electrons, protons, neutrons and ions as well as photonic radiation such as gamma rays and x-rays.

Electromagnetic pulses (EMPs) can also cause problems. These can arise from nuclear explosions, lightning or other events which cause an electric or magnetic field or an induced electric current.

Apart from the space environment, electronics may be subject to radiation in applications such as nuclear reactors (eg, control systems), particle accelerators, high-altitude aircraft, high-altitude balloons, x-ray machines, food irradiation machines (for preservation) and radiotherapy machines for medical applications.

Sources of radiation

Some potential sources of radiation, the particles produced, and the effects they have are:

- Cosmic rays – these are very fast particles which come from all directions in the universe. They consist of about 85% protons, 14% alpha particles (helium nuclei), 1% heavy ions as well as x-rays and gamma rays. Most of these are filtered by the atmosphere and therefore mostly spacecraft are affected; however, collisions between cosmic rays and particles in the Earth's atmosphere can also generate secondary radiation which can reach the surface.
- The Van Allen radiation belts surrounding the Earth contain electrons and protons, mostly from the Sun, which are trapped by the Earth's magnetic field. The strength of the radiation in these belts varies enormously. Spacecraft are affected by them, and they are also hazardous to astronauts. (Fig.2)
- Solar flares eject particles such as protons and heavy ions as well as x-rays, some of which reach the Earth's atmosphere. These can be associated with solar storms or geomagnetic storms.

Opposite: an artist's concept of the NASA Lunar IceCube spacecraft to be launched in 2020. It is a 6U CubeSat that uses a Space Micro Proton400K radiation-hardened single board computer (Fig.1; inset).
Image credit: Recentcontributor2000.

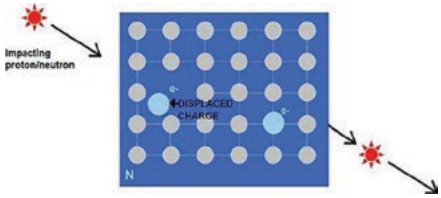


Fig.3: a proton or neutron impacting a semiconductor crystal lattice can displace an atom from its correct location and alter its electronic properties. Meanwhile, it continues through the crystal (with reduced energy), where it can potentially cause additional damage or electronic disruption.

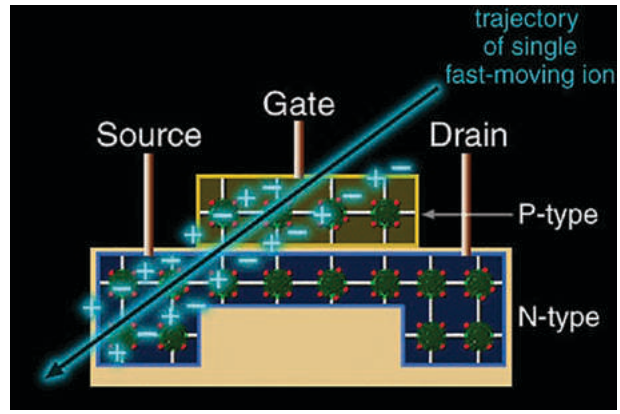


Fig.4: a radiation particle, in this case an ion, passing through a field effect transistor (FET) structure. This can disrupt thousands of electrons. The flow of current passing through the structure is affected, possibly causing a malfunction in the circuit. The damage is usually temporary. *Image courtesy Windows to the Universe.*

- Secondary particles can be generated by the interaction of primary particles when they enter electronic structures, eg, a cosmic ray which strikes the encapsulation of a device.
- Gamma and neutron radiation is produced in nuclear reactors and can affect electronics inside a shielded area.
- Particle accelerators such as the Large Hadron Collider produce various types of radiation that can affect unshielded sensors and control circuitry.
- Nuclear explosions can produce a powerful electromagnetic pulse and a large variety of particles that can affect electronics and power grids.
- Trace radioactive elements in electronic chip packaging and wafer materials were found to be a problem in the 1970s. Alpha particles (helium nuclei) in older packaging materials could discharge the capacitors in DRAM, but this effect has been minimised today by using purer packaging materials and more sophisticated error correction.

Origins of damage or effects to electronic materials

Radiation damage or effects to electronic materials may be either permanent or temporary while the source of such radiation can be in the form of neutrons, protons, alpha particles, ions, x-rays, parts of the UV spectrum and gamma rays.

In terms of damage to electronics radiation can be divided into two main types. One type is high energy radiation which is capable of causing disruption of atoms in a device's crystal lattice and permanent damage. The other type is that comprising of lower energy radiation that is not able to cause disruption in a crystal lattice but can cause disruption of electronic charge carriers in a crystal lattice.

Permanent damage can be in the form of "lattice displacement" whereby atoms are moved from their correct positions, causing the formation of new electronic structures such as recombination centres, and worsening the properties of semiconductor junctions due to rearrangement of charge carriers within the crystal.

Although such lattice displacement damage is usually permanent, in some cases limited self-repair is possible due to "annealing" whereby displaced atoms can move back or partially back to their correct locations.

Individual instances of lattice displacement won't necessarily cause noticeable degradation of a device.

However, the effect is cumulative and multiple instances of lattice displacement cause long term degradation in the performance of a device.

This could include, for example, alteration of the switching threshold voltage of a transistor, causing a transistor to remain permanently switched on or off, or reducing the output of a solar cell on a spacecraft.

Another source of damage in semiconductor crystal materials is ionisation. The energy of particles involved in ionisation effects is generally too low to cause permanent damage but can create "soft errors" such as corruption of memory contents or alteration of circuit logic states (Fig.4).

The damage can become permanent if a condition is generated such as a Single Event Latchup (SEL), which can lead to permanent damage under certain conditions (more on that later).

Main types of radiation-induced effects

Based on the above mechanisms, radiation effects in electronic structures can be broadly categorised as:

Soviet 'retro' radiation hardening technology

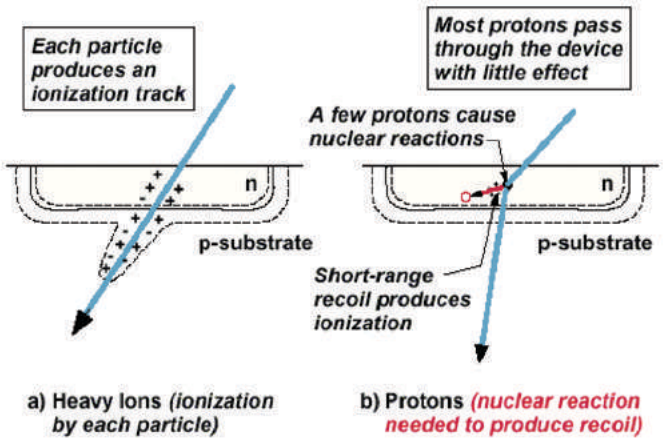
When a Soviet pilot flying a MiG-25 defected to the West in 1976, experts were surprised to find that a majority of its avionics were built with vacuum tubes.

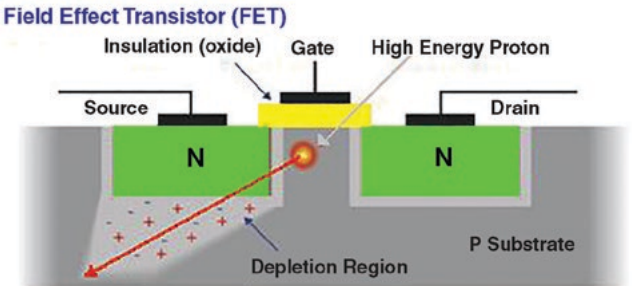
This represented old technology for the time, but it was concluded that the Soviet decision to use vacuum tubes was due to their better tolerance of temperature extremes than solid state electronics of the time.

It was also considered that this meant that the avionics bays would not need environmental controls, and vacuum tubes were also more resistant to the electromagnetic pulse (EMP) from nuclear explosions than solid-state devices.

Also, the tubes enabled the aircraft radar to operate at an extremely high power of 600kW. Having said that, at the time, the more modern electronics of the West was quite capable of withstanding adverse environmental conditions and EMP, so the real reason the Soviets used vacuum tubes was probably that their electronic industry was less advanced than that of the West.

But there are still situations today where vacuum tubes are considered for use in space-based applications, because of their robustness.


Each particle produces an ionization track
Most protons pass through the device with little effect
A few protons cause nuclear reactions
n
p-substrate
n
p-substrate
Short-range recoil produces ionization
a) Heavy Ions (ionization by each particle)
b) Protons (nuclear reaction needed to produce recoil)



Figs.5 & 6: a Single Event Upset, whereby a heavy ion or proton passes through a memory element, creating electron and hole pairs due to ionisation within the crystal lattice. This creates a parasitic current which can alter the value of the bit stored in memory (a bit flip). In the case of a proton passing through the structure, secondary nuclear reactions can lead to further effects. *Source: NASA.*

1) Lattice displacement effects; described above
2) Total ionising dose effects; a cumulative effect of radiation causing long term damage
3) Transient effects, such as the short but intense pulse caused by a nuclear explosion which may or may not cause permanent damage
4) System-generated EMP effects which can result in destructively high currents
5) Single-event effects (SEE) – probably the most significant events electronics are subject to

Single Event Effects

SEE is the general term for a variety of phenomena such as the ionisation effects described above, in which a single energetic radiation event has some effect on the electronic state of an electronic structure. Single Event Effects can be classified as follows:

Single Event Upset (SEU) – "soft" errors which result in no permanent electronic damage. SEU errors often manifest as 'bit flips' in memory, ie, a zero changing to a one or vice versa. In some cases, multiple bits can be affected. This can also result in inappropriate pulses in circuitry (see Figs. 5 & 6). SEU can potentially place the affected circuitry in some undesired mode such as a test mode, a program execution halt or some other unwanted state.

An SEU can be cleared, if detected, by a computer or equipment reset, or by re-writing the affected bit with its original value, which was famously done in the Voyager spacecraft; see below.

Single Event Latchup (SEL) – this can be either a "soft" or a "hard" error. A hard error can lead to the destruction of the device.

In an SEL, a circuit element is forced into a high-current state, causing excessive heating beyond a device's operational limits (see Fig.7). This could result in its destruction (hard error) unless the fault is quickly detected and the device is reset by power cycling.

This type of effect was first noted in 1979, and it can be caused by heavy ions or protons.

Note that the commercial radiation-hardened chip (GR712RC) mentioned below has circuitry to monitor junction temperatures which can shut down and reset the device in this case.

Single Event Burnout (SEB) – this is a "hard" error which destroys the device.

Devices such as power metal oxide semiconductor field effect transistors (Mosfets) were thought to be the only ones affected by this, but it is now known that other devices such as power bipolar junction transistors (BJTs), insulated gate bipolar transistors (IGBT), thyristors, high-voltage diodes and CMOS PWM controllers and drivers are also susceptible.

This destructive mode of failure is due to the passage of heavy ions or other particles, which may originate in solar radiation, through sensitive regions of the device.

SEBs in power Mosfets have been known to occur in space-based electronics since 1986, but more recently, have been recognised as a possible source of failure for terrestrial devices as well.

An SEB event occurs when a high-voltage semiconductor device is biased in an off state with a voltage close to its maximum rated value applied.

A single ionising particle then strikes the depletion region of the device, generating a series of electron-hole pairs.

If the electric field in that region is strong enough, an avalanche or regenerative feedback effect is initiated, causing destructively high currents in the device.

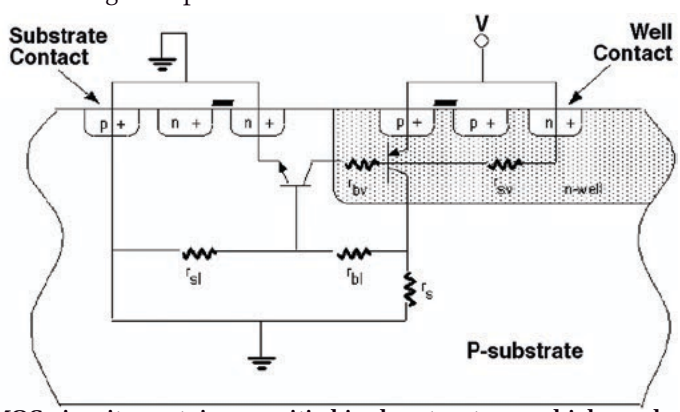


Fig.7: CMOS circuits contain parasitic bipolar structures which can be triggered by transient signals from radiation. Such circuits are protected by guard bands and clamps, but radiation signals can bypass these. Two parasitic transistors are shown in a four-layer device. If triggered, several hundred milliamps can flow, leading to rapid heating and destruction if this is not detected and stopped within milliseconds. SEL is more likely at higher temperatures. *Figure courtesy NASA.*

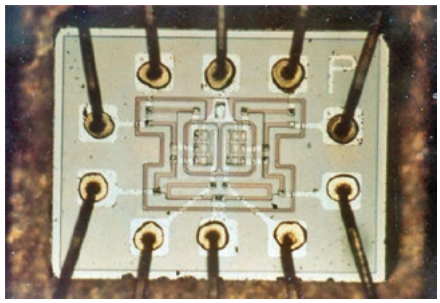


Fig.8: the Fairchild Micrologic Type G three-input NOR gate from 1961, the first practical integrated circuit, as used in the Apollo guidance computer. During its manufacture, the price dropped from US$1000 to US$20, leading to its commercial use. It's intrinsically radiation-resistant due to its large size and small component count (six transistors and eight resistors). To see how this chip worked and how it got humanity to the moon see: siliconchip.com.au/link/aapx

Only N-channel Mosfets seem to be affected by SEB; P-channel devices appear to be immune.

Single Event Gate Rupture (SEGR) – this affects power Mosfets and is caused by the breakdown of the oxide layer on the Mosfet gate structure. The results are similar to an SEB event.

Electrostatic charging of spacecraft

Spacecraft can acquire an electrical charge due to their interaction with charged particles in space.

Generally, spacecraft have a positive charge on the sunlit side due to the photoelectric effect, and a negative charge on the dark side due to plasma charging.

This charge can occur either on the surface of or internal to the spacecraft. This can result in damage to electronic circuitry and interference with scientific measurements.

Damage can occur due to electric discharges between adjacent components at very different potentials, or from an electric discharge due to an accumulated static charge within dielectric materials due to long-term bombardment with charged particles.

The satellites most vulnerable to these effects are in geosynchronous orbit, where there is a low plasma density that does not allow a bleed-off of charge.

Potentials as high as 20kV have been recorded.

Spacecraft charging avoidance options are limited, but it can be mitigated by having charge dissipating surfaces, using design practices to minimise differential charging and careful consideration of spacecraft orbit and space weather during launch (eg, avoiding solar storms).

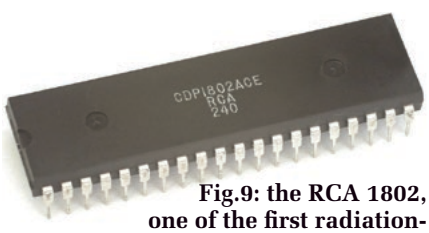


Fig.9: the RCA 1802, one of the first radiation-hardened CPU chips. *Image credit: CPU collection Konstantin Lanzet, CC BY-SA 3.0* **siliconchip.com.au/link/aapy**

Electromagnetic pulses

Apart from nuclear explosions, electromagnetic pulses (EMP) can arise from lightning, electrostatic discharges, switching heavy current loads, non-nuclear electromagnetic pulse (NNEMP) weapons and electromagnetic forming, as used in industry to shape certain items.

An EMP can induce strong currents in materials and damage or destroy them, wipe magnetic media, interfere with wireless communications, destroy national power grids and have many other adverse effects.

Protection against EMP can include shielding and current limiting devices, but it is difficult to protect an entire power grid.

Recognition of such a risk has lead to the US "Executive Order on Coordinating National Resilience to Electromagnetic Pulses" (see **siliconchip.com.au/link/aapz**).

See also the report at: **siliconchip.com.au/link/aaq0**

It is not known if Australia has any specific plans to deal with such threats.

Designing to minimise radiation-induced events

Avoidance or minimisation of adverse events due to radiation can be achieved through appropriate component selection, digital error detection and correction, use of redundant components, detection of excessive current or heat at chip junctions (see Fig.11) and also shielding.

The problem with shielding is that it is heavy and is also ineffective against cosmic rays. It can, however, be effective against solar flare particles.

Components designed explicitly for radiation hardness are typically based on a commercial equivalent, with various modifications.

They generally lag behind non-hardened devices in performance, partly because of the extra research, development and certification required to produce them and also because some radiation hardening features tend to lower performance.

In fact, older, slower devices tend to tolerate radiation better due to their larger junctions, so 'upgrading' space-rated components is much more difficult than their terrestrial counterparts.

In terms of susceptibility to radiation-induced effects, technologies in order of the least susceptible to the most susceptible are as follows: CMOS (silicon on sapphire), CMOS, standard bipolar, low-power schottky bipolar, nMOS DRAM (n-type metal oxide semiconductor dynamic random access memory).

Radiation hardening of devices can be characterised as being based on physical methods or logical methods, such as error correction and redundancy.

Physical hardening methods include:

- fabricating chips on an insulating substrate such as sapphire, to reduce the possibility of parasitic stray current pathways caused by radiation events
- the use of bipolar transistors in integrated circuits which use two types of charge carriers instead of FETs, which use just one
- the use of SRAM (static random access memory), which is intrinsically more radiation-resistant than DRAM (dynamic random access memory), although it is larger and more expensive
- the use of wide band-gap semiconductors such as gallium nitride and silicon carbide instead of silicon, which are less likely to be disrupted by a given electrical charge injection
- shielding of electronics with materials such as aluminium and tungsten, despite the added weight
- shielding of electronics with boron-11, which results in less secondary emission of radiation when struck by primary radiation

Logical means of radiation hardening include:

- the use of strong error correct-

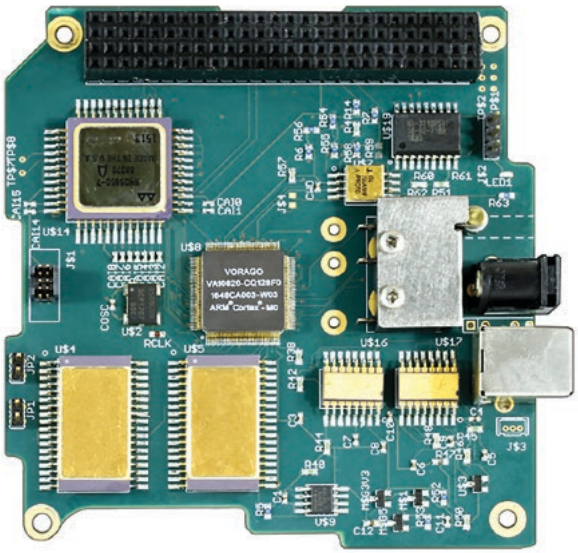


Fig.10: the radiation-hardened Vorago RH-OBC-1 onboard computer and avionics board for spacecraft, specifically designed for CubeSats.

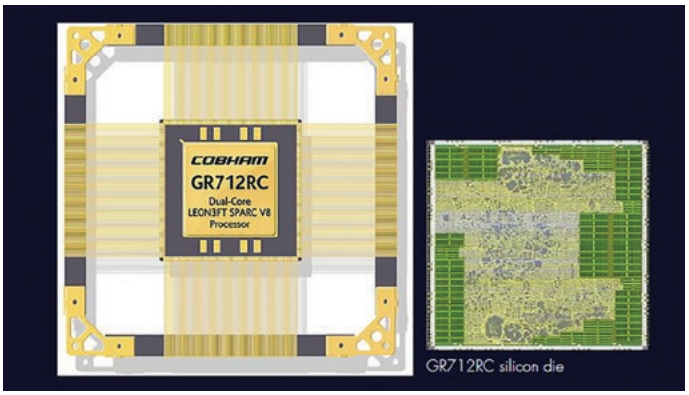


Fig.11: the Ramon GR712RC, a radiation-hardened chip for space applications. It contains a dual-core LEON3FT SPARC V8 processor and was being used by the SpaceIL "Beresheet" lunar lander (see SILICON CHIP, November 2018; siliconchip.com.au/Article/11296). It uses Ramon's proprietary "RadSafe" technology, with a dedicated design including circuitry to monitor radiation, monitoring of chip junction temperatures, error correction logic, hardened flip-flops, redundant circuit elements and a watchdog timer to reset of the chip if it crashes.

ing schemes for memory, such as the BCH (Bose–Chaudhuri–Hocquenghem) cyclic error correction scheme. BCH (250, 32, 45) can provide 99.9956% correctness even with a 10% memory bit error rate (1 byte in every 711 would still be defective). Robust error correcting codes have a high computational overhead.

- the use of redundancy such as multiple redundant computers and software, as used on the Space Shuttle. With three or more computers, they can 'vote' if they do not all agree (see below)
- the use of multiple error correction schemes
- keeping multiple copies of critical information
- the use of a watchdog timer that will reset a computer if the expected behaviour does not occur after a certain amount of time

Testing techniques

Electronic components can be tested for radiation hardness by exposing them to radiation from sources such as particle accelerators, radioactive elements like californium and actual testing in space. The correct application of statistical techniques to determine true error rates is very important.

Radiation and CubeSats

CubeSats are popular, low-cost satellites often built on a tight budget and with commercial off-the-shelf (COTS) components.

The question is often asked if radiation hardening of CubeSats is necessary.

The answer varies depending on the CubeSat mission, but in general, CubeSats have limited lifetimes in low earth orbit, where radiation is a much less serious threat than in other orbits.

The limited expected life in orbit also limits the requirement for extensive radiation hardening measures. Radiation hardening in CubeSats is usually achieved through software, component redundancy and good component choices.

A standard Android phone has been used as the control device on a CubeSat.

On the other hand, the Lunar IceCube CubeSat mission to the moon uses a radiation-hardened computer – see photo on page 12.

For more information on CubeSats, refer to the SILICON CHIP article on that topic in the January 2018 issue (siliconchip.com.au/Article/10930).

Commercial radiation hardened devices, past and present

As mentioned above, early electronic devices were less susceptible to radiation because of their large feature sizes.

One such example is the Fairchild Micrologic Type G three -input NOR gate from 1961, as used on the Apollo guidance computer (see Fig.8).

The RCA 1802 from 1976 (Fig.9) was one of the first microprocessors available in a radiation hardened version, fabricated using silicon on sapphire. It used the Complementary Symmetry Monolithic Array Computer (COSMAC) 8-bit architecture.

The chip is still made today by Intersil, and sold as a high-reliability device, although its exact radiation resistance is unstated.

It was and is used in the Galileo Probe, Hubble Space Telescope, Magellan spacecraft and various other satellites.

The processor, in its bulk silicon version, was also popular with hobbyists. Further information on this chip is at the following links: siliconchip.com.au/link/aaq1 (device history) and siliconchip.com.au/link/aaq2 (regarding its use in amateur radio satellites).

The Space Shuttle had a Data Processing System which comprised four IBM AP-101S General Purpose Computers with identical hardware and software, and a fifth computer with identical hardware but different software which had the same goals as the software in the other four computers.

The computers would vote on any result, and any system in disagreement with the others would have its result excluded.

While not explicitly stated, it is likely that this voting system took into account the possibility of data processing errors due to radiation events or for other reasons and the redundancy would ensure a correct result.

A description of the system can be seen at: siliconchip.com.au/link/aaq3

Two current devices of interest that are radiation-hardened for space ap-

Fig.12: a photo of the Starfish Prime nuclear explosion (400km altitude) taken 45-90 seconds after detonation in 1962. It caused an unexpectedly strong electromagnetic pulse which destroyed several satellites and land-based electrical devices.

plication are the Vorago RH-OBC-1, designed for CubeSats (Fig.10), and the Ramon GR712RC (Fig.11

Notable radiation-induced events

Some notable events due to radiation interacting with electrical apparatus or electronics are as follows:

1. Geomagnetic storm, 1859: A geomagnetic storm (also known as a solar storm) occurred on 1st & 2nd September 1859. This resulted in numerous sunspots and solar flares.

What is assumed to be today a coronal mass ejection (the expulsion of charged particles from the sun) then resulted in induced currents in telegraph wires, which caused shocks to operators and also started some fires.

This storm was also known as the "Carrington Event".

The Aurora was seen as far north as Queensland.

The original 1859 Moreton Bay Courier newspaper article about the aurora can be seen at: siliconchip.com.au/link/aaq4

2. The Starfish Prime nuclear test: In 1962, the United States conducted high-altitude nuclear tests, detonating a 1.4 megatonne nuclear warhead 400km above the Pacific Ocean, 1450km from Hawaii (see Fig.12).

The explosion caused an unexpectedly large electromagnetic pulse, resulting in electrical damage in Hawaii, destroying 300 street lights, setting off burglar alarms and destroying a microwave link.

Bright auroras were also observed in the detonation area and in an area on the opposite side of the Earth from the detonation area.

Apart from the electromagnetic pulse, the explosion also produced beta particles (electrons) which persisted as an artificial radiation belt within the earth's magnetic field until the early 1970s.

The failure of many satellites was attributed to the energetic electrons injected into the Earth's magnetic field by this detonation.

These satellites included Ariel, TRAAC and Transit 4B, while the first commercial communications satellite (Telstar) was damaged, ultimately leading to its complete failure in 1963. The Russian Kosmos V satellite was also damaged, among others.

A video about the Starfish prime explosion titled "Operation Dominic I and II - Starfish Prime Part 2 1962" can be seen at: siliconchip.com.au/link/aaq5

3. Radioactive decay in electronics chip packaging: Errors from trace radioactive materials in electronics chip packaging and silicon came to be recognised as a significant problem in the 1970s.

Alpha particles (helium nuclei) are a common result of radioactive decay but are sufficiently slow and massive that they generally cannot penetrate the housing of electronics (they are even stopped by clothing or a sheet of paper).

However, alpha particles originating from that packaging itself can interface with and affect the electronics within.

A very low alpha particle flux of 0.001 counts/hr/cm^2 are required to minimise the problem. This is be-

Finding out about "space weather"

Spacecraft operators and operators of certain other sensitive equipment are concerned with anomalies caused to electronics by radiation.

Radiation from space comes under the auspices of "space weather", and several websites have been established where information on conditions can be obtained.

Some such websites, including one from the Australian Government, are as follows:

www.sws.bom.gov.au/Space_Weather

www.spaceweather.com/

www.swpc.noaa.gov/

www.swpc.noaa.gov/products/seaesrt

Fig.13 at right shows an example of space weather data taken from the NOAA Spacecraft Environmental Anomalies Expert System – Real Time (SEAESRT).

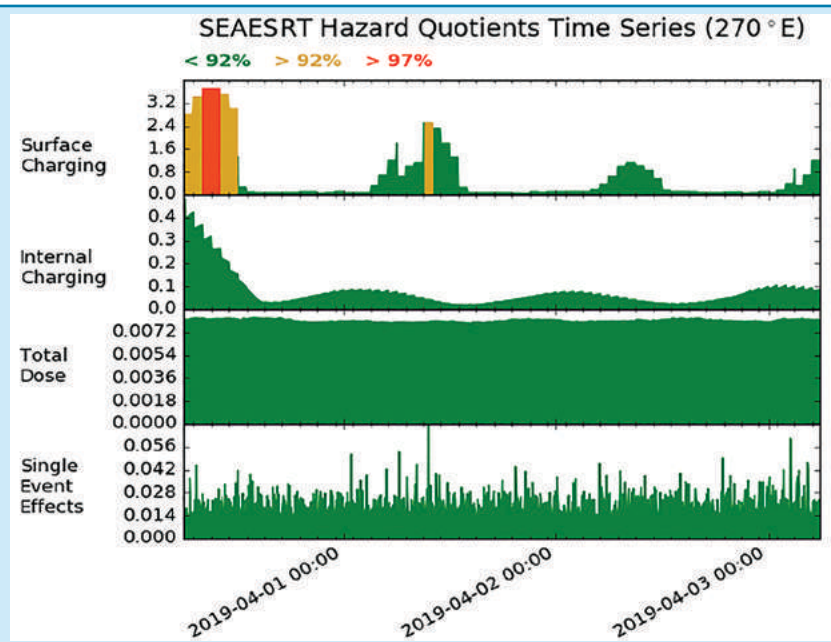
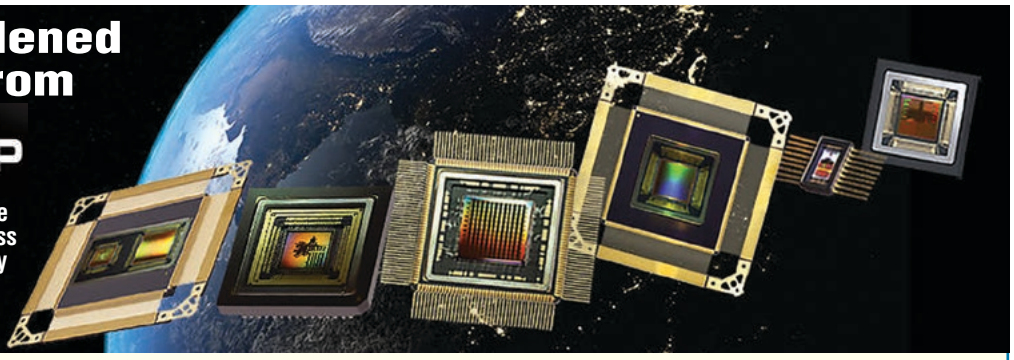


Fig.13: space weather is relevant to spacecraft operation. This screen grab shows a space weather readout from the NOAA website, for a satellite in geostationary orbit at 270°E.

Radiation-Hardened Atmel Range from MICROCHIP



As this issue was going to press, the following media release came across our desks. We're not sure how many readers would be into space and satellite applications but we thought it interesting nevertheless!

Designers of space applications need to reduce design cycles and costs while scaling development across missions with different radiation requirements. To support this trend, Microchip Technology Inc.has introduced the space industry's first Arm-based microcontrollers (MCUs) that combine the low-cost and large ecosystem benefits of Commercial Off-the-Shelf (COTS) technology with space-qualified versions that have scalable levels of radiation performance.

Based on the automotive-qualified SAMV71, the SAMV71Q21RT radiation-tolerant and SAMRH71 radiation-hardened MCUs implement the widely deployed Arm Cortex-M7 System on Chip (SoC), enabling more integration, cost reduction and higher performance in space systems.

The SAMV71Q21RT and SAMRH71 allow software developers to begin implementation with the SAMV71 COTS device before moving to a space-grade component, significantly reducing development time and cost. Both devices can use the SAMV71's full software development toolchain, as they share the same ecosystem including software libraries, Board Support Package (BSP) and Operating System (OS) first level of porting. Once preliminary developments are complete on the COTS device, all software development can be easily swapped out to a radiation-tolerant or radiation hardened version in a high-reliability plastic package or space-grade ceramic package.

The SAMV71Q21RT radiation-tolerant MCU reuses the full COTS mask set and offers pinout compatibility, making the transition from COTS to qualified space parts immediate.

While the SAMV71Q21RT's radiation performance is ideal for NewSpace applications such as Low Earth Orbit (LEO) satellite constellations and robotics, the SAMRH71 offers the radiation performance suited for more critical sub-systems like gyroscopes and star tracker equipment.

The SAMV71Q21RT radiation-tolerant device ensures an accumulated TID of 30Krad (Si) with latch up immunity and is nondestructive against heavy ions. Both devices are fully immune to Single-Event Latchup (SEL) up to 62 MeV.cm²/mg.

The SAMRH71 radiation-hardened MCU is designed specifically for deep space applications.

tween 100 and 10,000 times less than the emissions from the sole of a typical shoe.

4. Voting error in Belgium: In 2003 in Schaerbeek, Belgium, there was electronic voting for an election, and a single candidate obtained an extra 4096 votes. The apparent error was only noticed because that was more votes than was possible.

The error was blamed on a Single Event Upset (SEU) due to radiation, causing a bit flip (inversion of zero to one).

To explain how this can happen, recall that binary code is represented as bits (zero or one) in positions for 1, 2, 4, 8 etc.

Position 13 of a binary number represents a value of 4096. So if that bit flips from zero to one, for example, the binary number 0000000000000 (zero) will become 1000000000000 (decimal 4096).

5. Qantas QF72: On 7th October 2008, Qantas flight QF72 experienced two sudden, uncommanded pitch-down maneuvers at 37,000 feet altitude (11300m) which caused injuries to passengers, crew and damage to the aircraft. Investigators traced the problem to one of three air data inertial reference units, which sent incorrect data to the flight control systems.

The following causes were considered for the "upset" (as it is officially described): software corruption, software bug, hardware fault, physical environment, EMI from aircraft systems, EMI from other onboard sources, EMI from external sources and SEE (Single Event Effect).

All were rated "unlikely" or "very unlikely" to have occurred, except for SEE due to radiation, which was rated as "insufficient evidence to estimate likelihood".

You can read the comprehensive and fascinating report about the upset at: siliconchip.com.au/link/aaq6

6. Voyager 2 bit flip: On 22nd April 2010, the spacecraft Voyager 2 (see SILICON CHIP, December 2018; siliconchip.com.au/Article/11329) had a problem with the format of the scientific data being returned to Earth.

On May 12th, engineers retrieved a full memory dump from the Flight Data System computer, which formats the data to be returned to Earth. They found a single bit of memory had flipped to the opposite of what it was meant to be.

They reproduced this in a computer on the ground and determined it gave the same data format problems as were being seen from the spacecraft.

On May 19th, commands were sent to the spacecraft to reset the affected memory bit and on May 20th, engineering data received from the spacecraft was normal again.

Interesting Videos . . .

"Demonstration of the effects of radiation on a commercial video camera" siliconchip.com.au/link/aaq7

"Watch A GoPro Travel Through Extreme Radiation" siliconchip.com.au/link/aaq8

"Declassified U.S. Nuclear Test Film #62" – from 1962, about the effects of high altitude nuclear detonations: siliconchip.com.au/link/aaq9

How modern semiconductors are radiation hardened – by Duraid Madina

Pretty much all modern processors are fabricated with a CMOS process, ie, with a chip made up of N-channel and P-channel Mosfets formed from doped semiconductor layers and insulating oxide layers, plus metal layers to form the wiring which distributes power and signals between the transistors.

In CMOS devices, radiation can result in the accumulation of charge in the oxide layer, leading to a shift in the gate-source voltage for a given drain current.

NMOS devices typically see a lowering in the threshold voltage, increasing current when the device is both off and on. PMOS devices tend to get 'weaker', ie, higher gate voltages are required to turn the device on, and when on, the drive strength is decreased.

This is not the only way in which CMOS devices are degraded by exposure to high-energy particles: other processes tend to result in a linearisation of the drain current vs. gate voltage curve, which for both NMOS and PMOS devices leads to an increase in gate voltage required to turn the device fully on.

These defects are effectively permanent and will continue until the transistor is entirely unusable. It is quite easy to measure this damage; techniques such as deliberately timing-critical 'canary' logic paths, structures such as ring oscillators, or even parameters such as the total power consumed by a device can be monitored during operation, with changes indicating impending failure.

As CMOS circuits have continued to shrink in size, radiation strong enough to alter the electronic state of a circuit but not so strong as to permanently damage it has become a common concern. For a while, the decomposition of radioactive lead isotopes in solder joints was a significant source of single-event upsets, but these days, the dominant source of SEUs is exposure to cosmic radiation.

The digital circuits most sensitive to single-event upsets are those for which a voltage is used to indicate the state by a multistable circuit, such as in the classic six-transistor SRAM cell, where a pair of coupled inverters store a single bit of information and are isolated when not in use.

As the size of the four MOSFETs, the local interconnect, and the operating voltage has decreased over time, there has been a significant decrease in the amount of energy required for an energetic particle to change the state of such a bit cell. Non-array elements like latches and flip-flops, and other array memories including DRAMs and flash memories, are also susceptible.

One way that the reliability of these cells has been increased in the face of radiation is to spread the transistor gates over wider areas to ensure that ion strikes affect only a single node potential rather than two or more.

Fortunately, the decrease in size of CMOS circuits has also allowed an increase in complexity which can also be utilised to combat radiation-induced events. So in addition to lower level design techniques like the increased gate area mentioned above, it is also possible to add redundancy to critical flip-flop cells, or even add error detection and correction coding to critical registers.

Higher level protection techniques can also be used, including active software- or microcode-driven 'scrubbing' of critical memory contents, replicating critical logic blocks to operate in lock-step, with majority vote comparators, or 'stop and retry' logic which causes the processor to recalculate any results where the veracity of the previous calculation may be in question.

Where field programmable gate arrays (FPGAs) are used, or other chips with configurable logic blocks, it is also possible to perform 'online' reprogramming of any logic blocks where a fault has been detected.

In chips where robustness is critical, designers even go so far as to add 'fault injection' logic. This allows the fault mitigation techniques described above to be more rapidly and thoroughly tested, compared to what is possible with typical lab-based radiation tests.

An example: reliable instruction fetching

One critical function in any microprocessor is instruction fetching. The processor needs a continual supply of instructions to tell each of the processor's functional units what they should be doing at any point in time.

It's vital that this be done at high speed (otherwise the microprocessor might remain idle), but it is even more critical that this be done reliably, as a corrupt instruction could easily lead to a variety of different errors, including potentially subtle corruption of program state, rather than an immediate crash or hang.

To meet the speed requirement, instruction fetching is typically performed with a hierarchy of logic blocks, each 'closer to the action' than the next. At the top level is typically a high-speed instruction cache, which stores a limited number of the most frequently executed instructions, eg, the bodies of frequently-called functions.

If for any reason this top-level cache is unable to immediately provide an instruction to be executed, the result will be an undesirable stall of the microprocessor while the cache attempts to fetch instructions from slower cache levels, memory, or perhaps even a disk or network.

Due to its limited size and speed-critical nature, radiation hardening of a top-level instruction cache frequently involves maintaining a completely separate copy. This copy is kept physically separated from the original to the maximum practical extent, to ensure that a radiation strike corrupts only one of the copies.

For speed reasons, typically only the original is "plumbed through" to the processor's core functional units, and an independent unit is tasked with checking that both the primary cache and its copy provide identical results.

In case a mismatch is detected, a high speed "stop!" signal is asserted to pause the rest of the processor before a potentially incorrect instruction is executed. This remains asserted until a more complex mechanism (such as an error correcting code) provides a known-good instruction and restores this correct entry to both the original cache and the copy.

This "stop!" signal is frequently one of, and sometimes the most speed-critical path in the entire processor. Given that it toggles relatively rarely, it is often implemented using special, power-hungry, high-speed circuit techniques.

Moving away from the high-speed core of a processor, error-correction techniques which take correspondingly longer times to use are justified. As the size of caches and memories increases, making complete copies of these becomes less practical.

So lower-level caches and main memories are frequently protected with modified Hamming codes where, for example, 64 bits of data are encoded into 72 bits so that the corruption of any two of the 72 bits can be detected, and the corruption of any one of the 72 bits can be seamlessly corrected.

In a radiation-hardened environment, main memories are frequently guarded with additional, software-based scrubbers which continually calculate and recalculate checksums for instruction memory blocks, and compare those against known-good values.

These blocks can be encoded with quite complex codes, needing thousands or millions of machine cycles to correct an error, but can be designed in such a way as to virtually assure recovery of the original data whilst still maintaining a relatively low overhead in terms of space required to store the encoded data. SC

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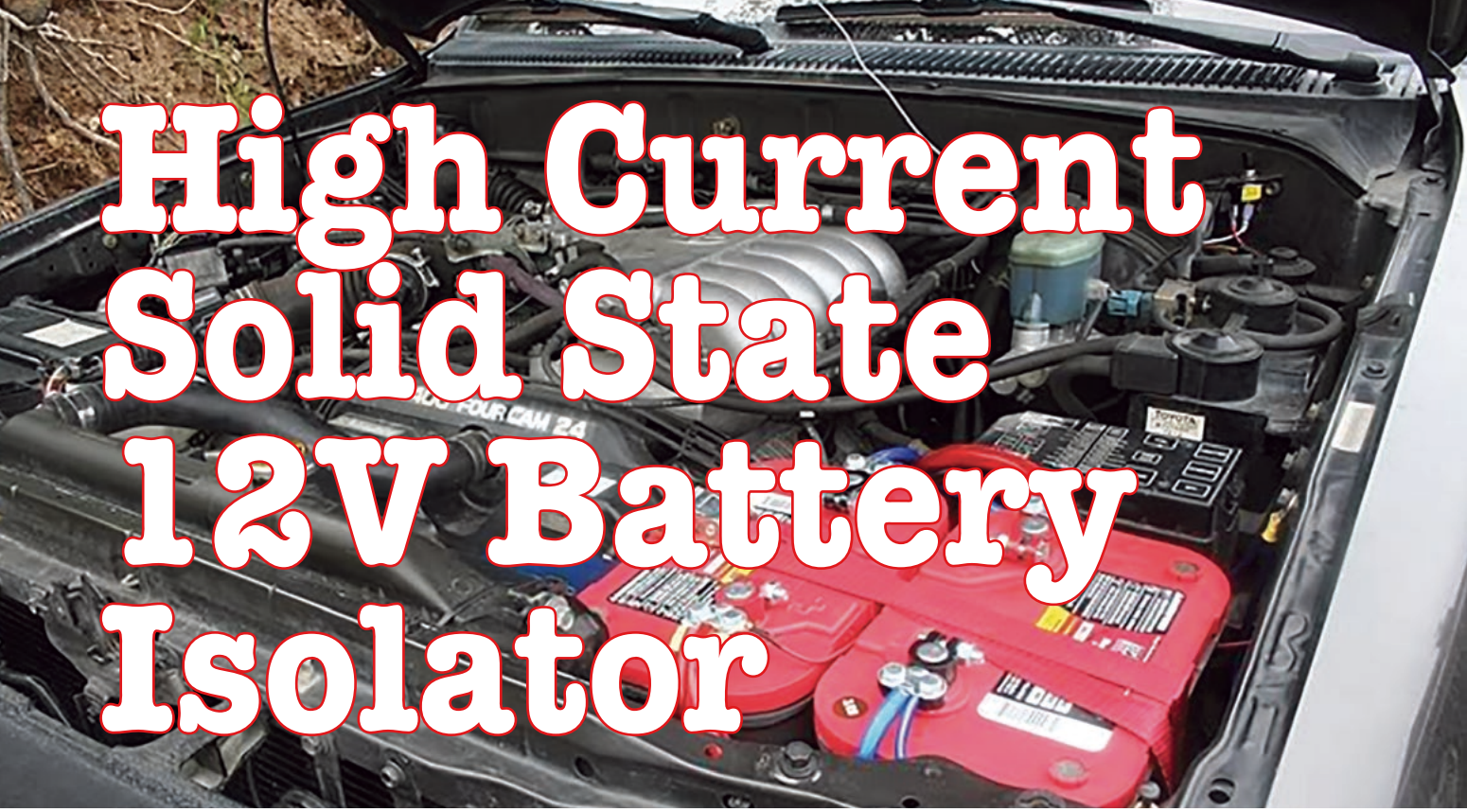


High Current Solid State 12V Battery Isolator

This device connects an auxiliary battery to the main vehicle battery/alternator while the engine is running, charging that extra battery. But it disconnects it once the engine shuts down, so that the vehicle battery can't accidentally go flat. It's cheap and easy to build but also very robust. It's ideal for RVs, campers, offroad vehicles and boats.

I have had ongoing problems with the battery systems on my 4WD vehicles. My car is fitted with an auxiliary 12V battery system that I use to run a fridge, some radios, camping lighting etc.

I tried using a commercial battery isolator to connect it to the main vehicle electrical system but found that this had two major shortcomings.

Firstly, its case offered little protection from the elements, and it occasionally filled with water – not good.

Secondly, it uses two open-frame style relays to connect the batteries in parallel. The contacts in these relays are nothing special and occasionally weld together, leaving the batteries permanently connected. That can lead to both batteries going flat. Also not good!

The idea of these isolators is to parallel the batteries when the engine is running and remove this connection when the engine is off.

So when you are camped overnight and you discharge the auxiliary battery, you can still start the engine in the morning.

It works by measuring the vehicle battery voltage, which is usually below 13V with the engine off and around 13.5-14.5V when the engine is running.

So when the voltage is high enough, it determines that the alternator is charging the battery and connects the auxiliary battery.

When the voltage drops, it detects that the engine has been stopped and breaks that connection.

Not being at all happy with the commercial units I tried, I decided to design my own.

My design criteria were:

- Low current drain from the main battery when the engine is off.
- Fully solid-state operation (no relays).
- A low forward voltage drop when switched on, minimising heating and power loss.
- Must not interfere with radios (ie, no RFI/EMI).
- Must use commonly available parts.
- Must handle very high currents without damage (>100A).
- A completely waterproof and dustproof housing.

These made the first design decision easy: Mosfets are an ideal solid-state switching device for large direct currents.

While P-channel Mosfets are easier to drive for high-side switching, N-channel Mosfets offer lower losses at the same price thanks to a vanishingly small 'on-resistance'.

So I decided upon six Infineon IRFS7434TRL7PP Mosfets, which have an on-resistance of less than 1mΩ (0.001Ω) and are each rated at 40V and 362A.

(I initially used similar IRFS3004-7PPBF devices in my prototype, but these have now been discontinued).

The S7434TRL7PP Mosfets come in a 7-pin D2PAK (TO-263) SMD package

by Bruce Boardman (VK4MQ)

Shown here without its connecting leads (with their insulating covers, they'd hide half the panel!) use of the isolator is simplicity itself: connect the "main" terminal to the "main" battery positive and the "aux" terminal to the "aux" battery positive, with a chassis connection provided through the diecast metal case secured to the vehicle. That's it! The LED will glow when the main battery voltage is high enough to charge the auxiliary battery.

with a large mounting tab, which serves as both the drain and thermal contact for the device, allowing heat to dissipate into the PCB.

Despite the impressive specifications, these devices cost under $4 each.

Circuit description

The circuit is shown in Fig.1. You can see the six power Mosfets (Q1-Q6) at the top, between the two battery positive terminals. They are not all connected in parallel, for an important reason.

All power Mosfets have an internal 'body diode' (also known as a parasitic diode or internal diode) which is an inherent part of their construction, and this allows current to flow in one direction even when the FET is switched off.

So to prevent unwanted current flow in either direction, the six Mosfets are arranged as three pairs (Q1-Q3 & Q4-Q6), which are connected in 'inverse series'.

This way, the body diodes of each set of three Mosfets are connected anode-to-anode and so block current flow in both directions, unless both sets of Mosfets are switched on.

In this case, all the body diodes are effectively shorted out. Despite the FETs having very high current ratings, three have been paralleled in each set as cheap insurance against failure.

For example, the isolator could happen to be switched on during engine starting and starter motor currents can be very high, and high currents can also flow when the auxiliary battery is first connected to the vehicle electrical system after being fully discharged.

A single LM339 quad comparator (IC1) is used for all control functions. This contains four standard comparators with open collector outputs, which go low when the voltage at the inverting (-) input is higher than the voltage at the non-inverting (+) input, and are high impedance the rest of the time.

That turns out to be quite useful in this circuit.

I chose a switch-on threshold of 13.4V and a switch-off threshold of 12.6V. The main battery voltage is applied to pin 4 of CON1 and to a string of resistors to ground, which forms a voltage divider. The top part of the divider is 11.5kΩ [4.7kΩ + 6.8kΩ] and the bottom part is 6.8kΩ. This gives a division ratio of 2.69 [(11.5kΩ + 6.8kΩ) ÷ 6.8kΩ].

So at the switch-on battery voltage threshold of 13.4V, that means that 4.98V is applied to pin 6 of comparator IC1b (very close to 5V), and at the switch-off threshold of 12.6V, pin 6 of IC1b sees 4.68V [12.6 ÷ 2.69].

A 5V reference voltage is supplied by linear regulator REG1, powered from the main battery via a 100Ω resistor, and this voltage is applied to pin 7 of IC1b, the non-inverting input. Initially, output pin 1 of IC1b is high but once the main battery voltage rises above about 13.4V, the pin 6 input voltage exceeds that of in 7 (ie, 5V) and so output pin 1 goes low.

This pulls current through the 4.7kΩ resistor and LED1,

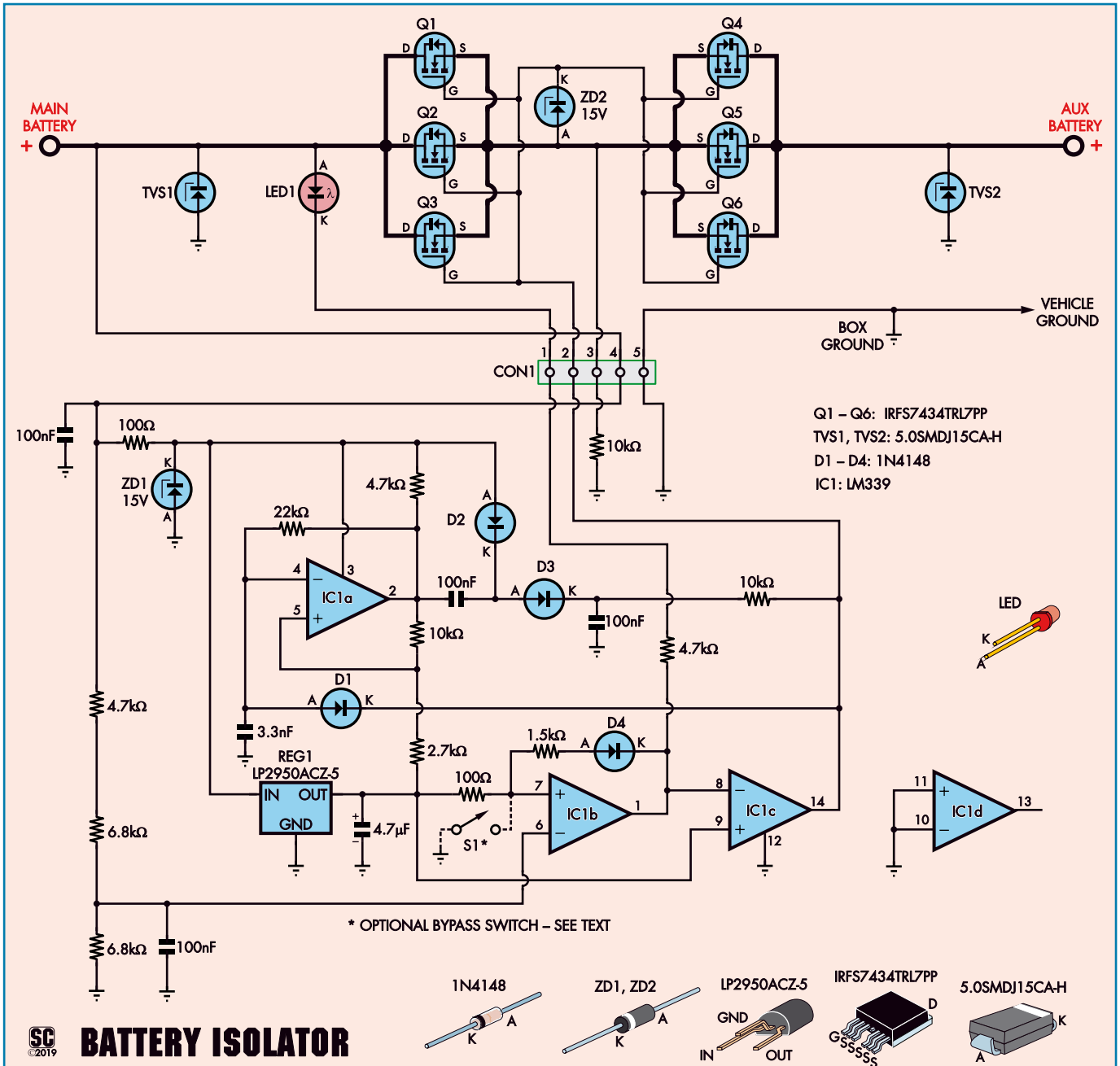


Fig.1: the circuit is basically a comparator which senses when the main battery voltage is high enough to charge the auxiliary battery and turns Mosfets 1-6 (or 1-12) on to do so. When the main battery voltage drops the Mosfets turn off.

so LED1 lights up.

In this condition, diode D4 is forward-biased and so the voltage divider formed by the 100Ω and 1.5kΩ resistors comes into play, reducing the voltage at pin 7 of IC1b from 5V down to about 4.69V (ie, 5V x 1.5kΩ ÷ [1.5kΩ + 100Ω]).

That has the effect of reducing the switch-off threshold to 12.6V (4.69V x 2.69) as desired.

That prevents the unit from switching on and off rapidly if the battery voltage is near either threshold.

The output voltage from pin 1 of IC1b is also fed to the pin 8 inverting input of IC1c, which has its pin 9 non-inverting input connected to the 5V rail, so it acts as an inverter.

So when the main battery voltage rises and IC1b's output goes low, IC1c's output goes high allowing the gates of the FET's to be pulled up via the 10kΩ resistor, switching them on (as described below) and connecting the two batteries.

REG1 is a micropower regulator, both to minimise the quiescent current but also (and most importantly) because it has an excellent initial tolerance of ±0.5%.

This, along with the 1% resistor tolerances, determines how accurate the switch-on and switch-off voltage thresholds will be.

Note that if you change the battery sense voltage divider resistors, you can calculate the new switching thresholds by calculating the divider ratio, then multiplying 5V and 4.7V by this ratio.

To change the hysteresis (ie, the spread of these two thresholds), you would need to change the value of the 1.5kΩ resistor at pin 7 of IC1b; a lower value gives more hysteresis, and a higher value, less hysteresis.

Mosfet gate drive

To switch on an N-channel Mosfet, the gate needs to be driven several volts above the source.

In this circuit, all the Mosfet sources are connected together and when the Mosfets are switched on, they will all rise to the battery voltage – ie, around 12V.

Therefore, the gates need to be driven to at least 17V and ideally higher, to 20V or more, to ensure that they switch on fully and have the lowest possible resistance and dissipation.

This voltage is generated by comparator IC1a, which is configured as an astable oscillator and drives a charge pump. The frequency of this oscillator is set to around 15kHz by the combination of the 22kΩ feedback resistor and 3.3nF timing capacitor.

Output pin 2 of IC1a is pulled high by a 4.7kΩ resistor, and the resulting square wave causes the 100nF capacitor to charge up to around 12V, via diode D2, when output pin 2 goes low.

When that pin goes high, to around 12V, the anode of diode D3 is lifted up to around 22V and this voltage in turn charges the following 100nF capacitor which supplies the Mosfet gates with about 20V via the following 10kΩ resistor.

That is, as long as output pin 14 of inverter IC1c is not being held low. If it is, this shunts any current flowing through that 10kΩ resistor to ground, holding the gates low.

At the same time, to save power, when pin 14 goes low, diode D1 becomes forward-biased and this discharges the 3.3nF timing capacitor, disabling the oscillator which generates the gate drive voltage. Zener diode ZD1 protects IC1 from supply spikes, in combination with the 100Ω series resistor from the main battery, which limits the current through ZD1 should it conduct. Zener diode ZD2 protects Mosfets Q1-Q6 from damage due to excessive gate voltages.

This is important as when the ~20V gate drive is initially applied, their sources are at 0V, and this could otherwise exceed their maximum ±20V V_{GS} ratings. However, ZD2 will not conduct for long, as the source voltage will quickly rise, reducing V_{GS} to around 7-8V under steady state conditions.

Features & specifications

- Suits most 12V batteries
- Waterproof
- Silent
- Solid-state (no relays)
- Easy construction and installation
- Switch-on voltage: 13.4V (13.13-13.67V*)
- Switch-off voltage: 12.6V (12.35-12.85V*)
- Quiescent current: approximately 3mA when off, 7mA when on
- High current handling (>100A peak, >40A continuous)
- Low voltage drop: typically <1mV/A
  Low dissipation: typically <1W @ 30A

*if some ±0.1% resistors are used (see parts list)

TVS1 and TVS2 are transient voltage suppressors, similar to zener diodes but more robust. These protect the unit and especially the Mosfets from high-voltage transients which are common in the automotive environment.

Construction

The prototype was built on two boards, with the control circuitry on a piece of stripboard and the Mosfets, TVSs and battery connectors soldered to a double-sided 'blank' PCB which was manually cut into large, isolated sections of copper that the components were then soldered to.

You can also build it this way, and we will give some information later on how to do so.

However, to make your life easier, we have produced two commercial double-sided PCB designs. Again, one is for the control circuitry and the other for the larger components.

You then just need to solder the components to these two boards, join them and mount them in the case.

Fig.2 shows the control board while Fig.3 is the Mosfet board overlay diagram. Use these and their matching photos as a guide during construction.

While the prototype had all six Mosfets on the same side

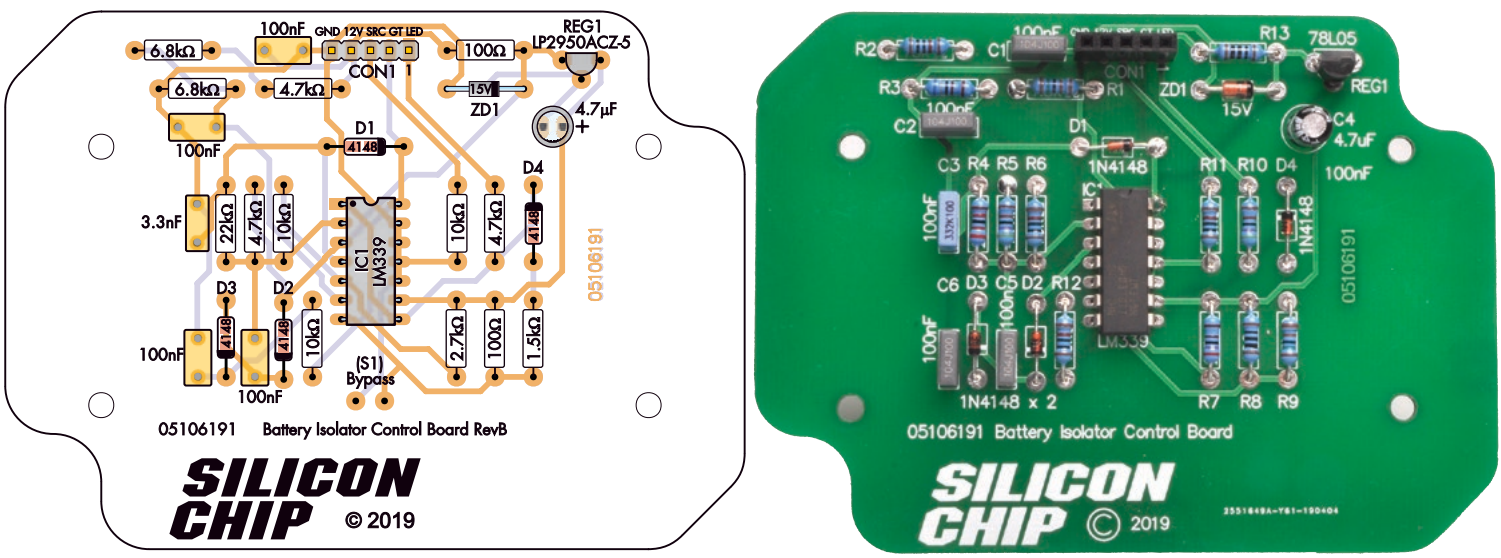
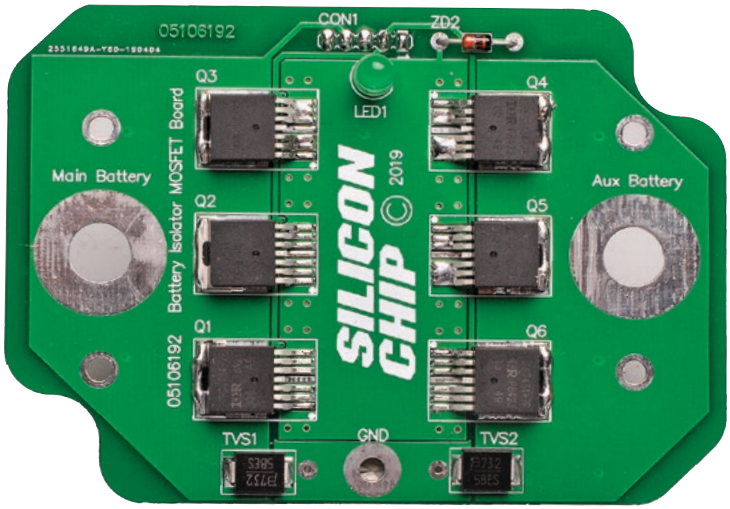
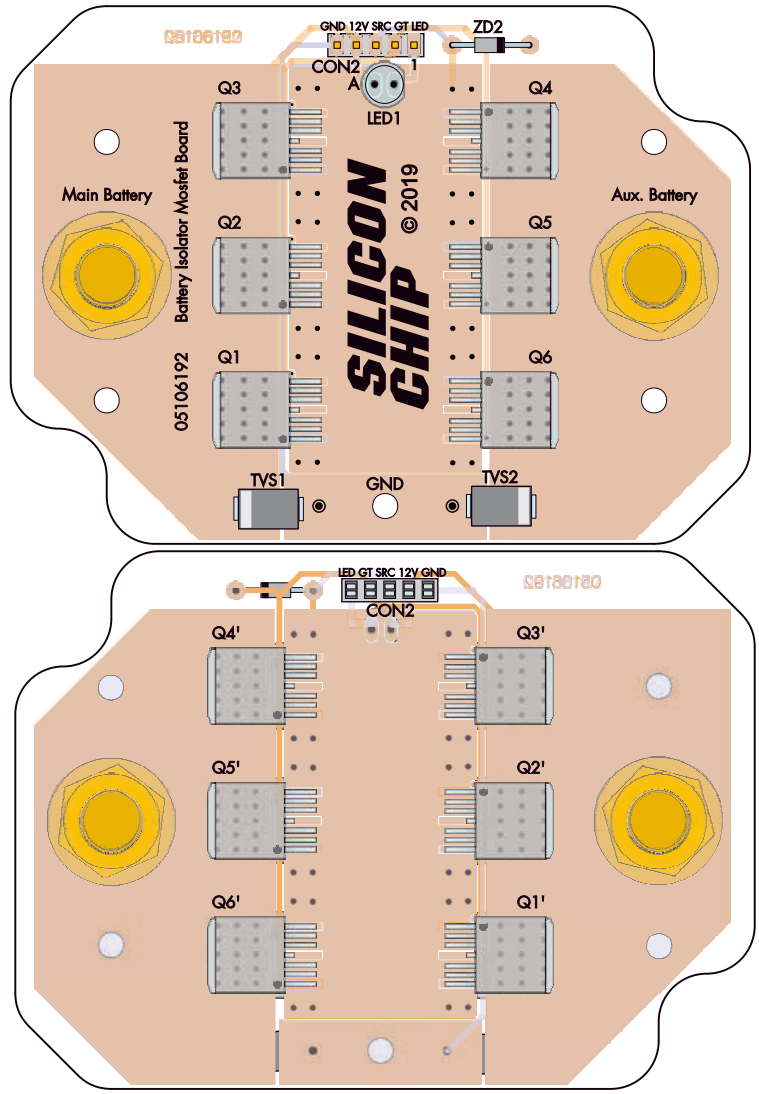


Fig.2: one of two PCBs in this project, the control board, with matching photo alongside. You could also build this on stripboard if you wished (see page 30) but PCBs make a much neater job and minimise the chance of errors.





Here's the top side of the completed Mosfet PCB. It's fitted with six Mosfets as shown in Fig.3a (top). But if you wish, another six Mosfets can be soldered to the underside of the PCB for even better current handling (Fig.3b, lower)

of the board, our Mosfet PCB (shown in Fig.3a) actually has twelve possible Mosfet mounting locations; six on the top and six on the bottom, with each pair of Mosfets directly above and below each other (Q1 and Q1', Q2 and Q2' etc).

Fig.3b shows where the Mosfets can be mounted on the underside of the board.

This gives you the option to mount three or four Mosfets on one side of the board and the remainder on the other side, which will help to more evenly distribute what little heat is generated in the device, and may also make slightly better use of the copper, reducing losses slightly. But it's a minor advantage, and you could just as easily fit them all one side, which is what we did.

For the control board, install the resistors where shown, then the 1N4148 diodes, ensuring that in each case, the cathode stripe faces as indicated.

You can then fit the single zener diode, with its cathode stripe facing to the left. Next, solder IC1 to the board, ensuring that its pin 1 dot/notch face towards the top as shown. We don't recommend that you use a socket as these can cause failures over time.

Now fit the non-polarised capacitors, which can be either ceramic or MKT types, followed by the single electrolytic capacitor, with its longer positive lead through the right-hand pad (marked with a "+" symbol).

That leaves REG1 and CON1. Gently bend REG1's leads to fit the PCB pads, then solder it in place. CON1 is a regular 5-pin header that's soldered to the top side of the board. You can then move on to the Mosfet board.

Building the Mosfet board

This board has eight SMDs (six Mosfets and two TVS diodes) plus three through-hole components, not including the battery connections, which we'll explain below.

Start by soldering the Mosfets. These are quite large and are soldered to large, thick copper planes so you will need a hot iron to solder them.

In each case, start by spreading a thin layer of flux paste over all the pads, especially the large one for the tab. Then locate the Mosfet in position and solder its pin 1 (near the dot). This is the gate connection so should be the easiest to solder.

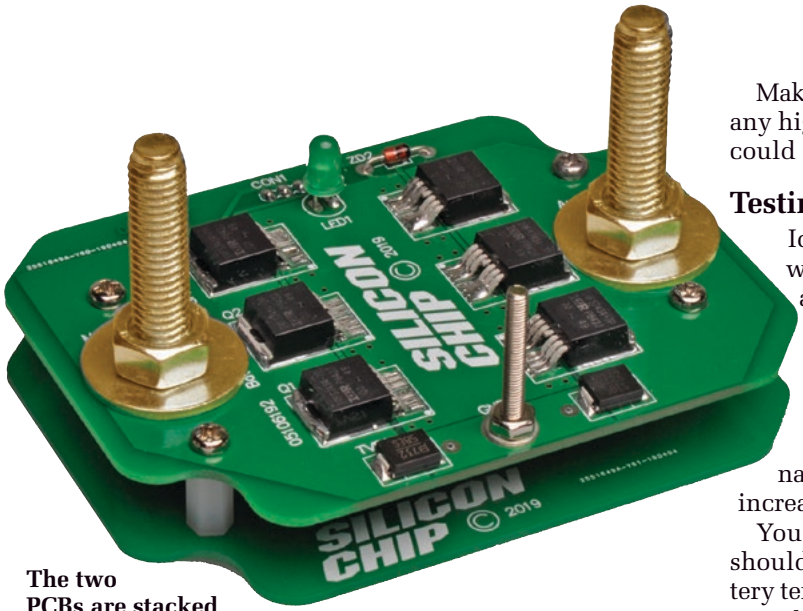
Check that all the pins and the tab are lined up correctly. If not, re-heat that solder joint and nudge the device slightly. Solder the remaining five small pins next. It doesn't matter if you accidentally bridge them to each other, as long as they don't bridge to the middle stub pin (which is not connected on this board) or pin 1 (the gate drive).

Finally, flow solder onto the junction of the tab and its large mounting pad underneath. You will need to apply heat and feed in solder until the solder flows to form a smooth fillet between the two. It's OK to add a little extra solder until it covers the tab. The flux you added earlier should aid in this process.

Repeat the above for the other five Mosfets. Then solder the two TVS diodes in place using a similar procedure, ie, applying flux paste to both pads, tacking the part down on one side, soldering the other side, then refreshing the first solder joint to ensure it is reliable.

Next, solder ZD2 and LED1 in place on the top side, with the orientations shown. It's a good idea to fit LED1 with some space between its lens and the PCB, so that it can poke through a hole in the case. The base of its lens should be a little bit more than the thickness of one M8 nut above the board.

Having done that, fit 5-pin header socket CON2 on the



The two PCBs are stacked as shown, with the 8mm brass battery connection posts fitted firmly in place with washers ensuring good contact with the PCB tracks.

underside of the board. The easiest way to do this is to plug CON2 into CON1 on the control board, attach the two boards using the four corner mounting holes, 12mm tapped spacers and short machine screws and then solder CON2 to the Mosfet board. That ensures the two headers line up properly.

The M8 brass screws that will be used as the battery terminals can now be fed through the Mosfet PCB, with a shakeproof or crinkle washer under the screw head (which goes on the bottom side of the board) and another under the nut which is done up tightly on the top side of the board.

This should give good electrical contact to the PCB and means that you don't need to solder the screws and nuts to the boards, which is difficult and makes disassembly impossible. (You can see that this was done on the prototype in the photos below.)

While the Mosfet board is now complete, you could consider adding some tinned copper wires in parallel with the copper on the board. This will reduce the voltage drop across the device, as well as its dissipation, and make it more robust.

However, we do not feel that this is strictly necessary due to the use of extra-thick 2oz copper on this board.

If you do want to run some extra wire, you can solder lengths of tinned copper wire from between pins 2 & 3 of each Mosfet to between pins 5 & 6 on the Mosfet on the other side of the board. You can then solder wires from the tabs of each Mosfet to the nearby battery terminal.

You may be able to solder these to the exposed copper around the nuts, or directly to the nuts themselves, with a very hot iron.

Make sure any added wires do not project above the board any higher than the bodies of the Mosfets; otherwise, they could potentially short to the metal lid of the case later.

Testing

Ideally, you should use an adjustable bench supply with current limiting for testing. Set it to 12V and around 50mA, then apply power between the main battery terminal and the ground pad on the Mosfet PCB (or pin 5 of CON1 or CON2). You should observe a current flow which settles at around 8mA. LED1 should remain off.

Measure the voltage at the auxiliary battery terminal relative to GND. It should be low, close to 0V. Now increase the supply to around 14V.

You should observe LED1 switch on. The current draw should increase slightly. The voltage at the auxiliary battery terminal should now have risen to the supply voltage.

Reduce the supply voltage back to 12V and confirm that LED1 switches off and the voltage at the aux battery terminal drops back to 0V within a few seconds. This verifies that everything is working as intended and you can now proceed to finish construction.

Adding a bypass switch

There may be times where the vehicle battery is low, but you still want to connect it to the auxiliary battery. One example would be if the vehicle battery is flat but the auxiliary battery is charged, and you want to 'jump start' the vehicle using the aux battery.

While you could do this with a screwdriver across the terminals, it's much nicer to have a switch which forces the unit to operate.

This is quite easy to do, but it does have one limitation in that this won't work if the vehicle battery is dead flat, since the unit is powered from it. But it should work down to at least 10V, or possibly even less.

The easiest way to achieve this is to connect a switch between pin 7 of IC1b and GND. When this switch is closed,

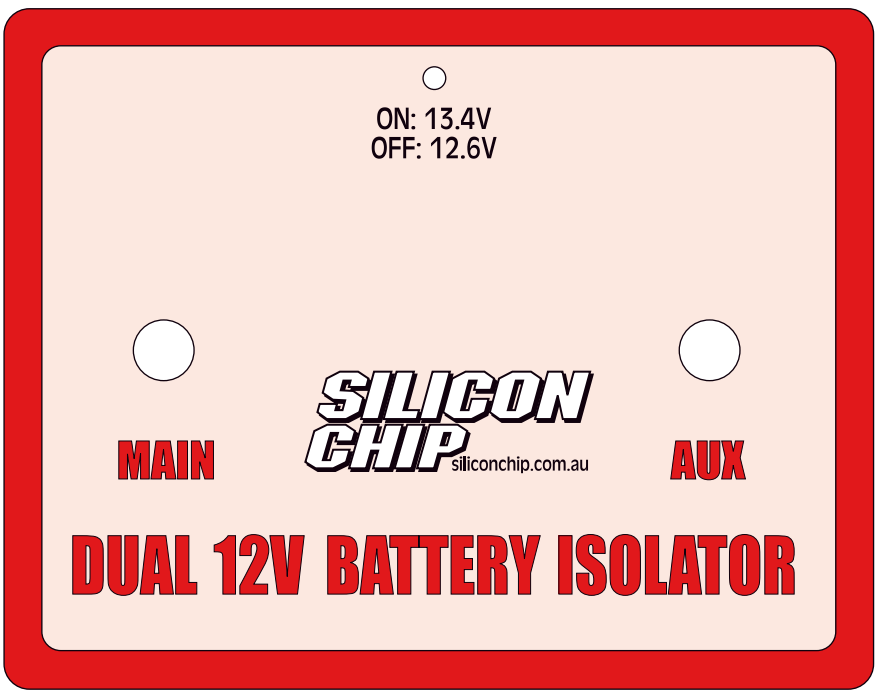


Fig.4: the front panel can either be photocopied or even better, downloaded from siliconchip.com.au/shop/11/5059 Ideally, it should be laminated before glueing in place.

Alternative construction method using stripboard and hand-cut PCBs

Instead of using the PCBs that we designed, you could copy the approach used for the prototype and build the control system on a piece of stripboard (Veroboard, for example) and hand-make your own PCB to host the Mosfets and related components.

My suggested stripboard layout is shown at right. This requires a board with at least 13 strips and 21 rows of holes. The diagram is drawn looking from the top of the board (ie, from the non-copper side). The copper tracks are shown as a visual aid, as if you can see them through the board.

You may want to use a larger piece of stripboard so that you have space to drill some mounting holes later. Before fitting the components, cut the tracks in the sixteen locations shown (including all seven tracks under IC1). It's often easier to cut the tracks with a 3mm twist drill, just removing the copper around the hole. Having soldered the components in place, fit the wire links.

The shorter links can be made using component lead off-cuts, or in some cases, by merely bridging adjacent tracks with solder. Longer links are best made with solid-core insulated wire (eg, Bell wire).

For the Mosfet board, you will need a piece of double-sided copper laminate around 100 x 100mm (slightly smaller, if you're planning to fit it into the specified box; check it fits before proceeding). Ideally, this should have thicker-than-normal copper (eg, "2oz" which is double normal PCB copper thickness).

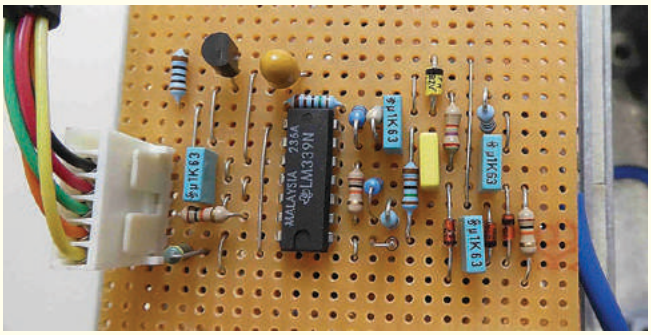
The required layout is shown clearly in the photos below. On the top of the board, you will need to make three straight cuts (eg, using a rotary cutting disc) to separate the copper into four islands.

The central islands should be around 25mm wide. Be careful not to cut through the fibreglass substrate; just the copper. Ensure the cuts are wide enough to guarantee electrical isolation. The underside requires just one cut down the middle, separating the copper on either side.

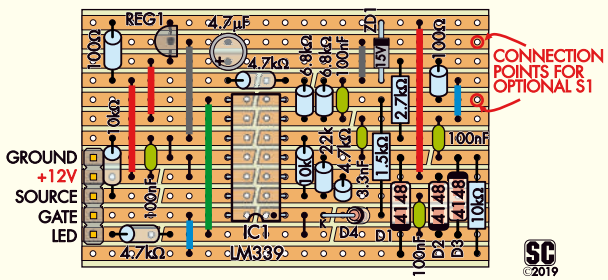
Next, drill two 8mm holes for the battery terminals and eight 2mm diameter holes (around the locations where the Mosfet tabs will be soldered) for wire vias to pass through later. Now is also a good time to drill four 3mm holes which the control board will be mounted to later (lining up with holes on that board).

Bend pin 1 (the gate) of each Mosfet up, then solder the remaining five small pins to the central island. Be careful to place the Mosfet so that the body does not bridge the cut in the copper plane. Then, using a hot iron, solder the tabs in place. Join the gates with light-duty wire; it's easier to use stiff bell wire, but you could use Kynar or multi-strand wire.

The small copper island at the bottom is the ground connection point. Solder the anodes of the two TVSs to this island, with the cathodes to the large planes on either side. You can now add the zener diode, with its anode to the large central copper area and its cathode to the Mosfet gate wire.



Stripboard prototype with matching layout below. Don't forget to cut the tracks where indicated – you'll have a massive short circuit otherwise!



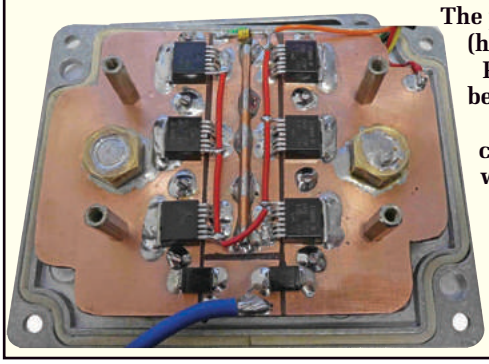
Next, run a strip of thick copper wire down the central island, soldered near every pair of Mosfets, plus wires on the underside fed through each of the 2mm holes you drilled earlier and bent over to touch the battery terminals. Solder them near the terminals and on both sides of the 2mm holes to form vias.

If you can't easily get thick copper wire, you can use a bundle with multiple pieces of 0.71mm or 1mm diameter tinned copper wire.

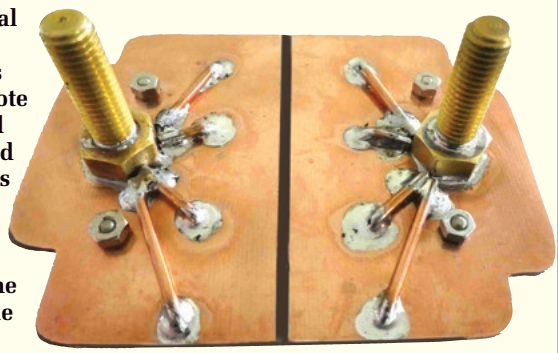
Solder four wires to this PCB: one to the main battery terminal side, to supply 12V to the control board; one to the small ground area, to connect to GND on the control board; one to the cathode of the zener diode, which goes to the gate drive pin on the control board; and one to the central copper island (or zener diode anode), which goes to the control board Mosfet source terminal.

Note, though, that this source terminal only connects to a 10kΩ resistor with the other end connected to GND. So you could make your life slightly easier by simply soldering a 10kΩ resistor between the two central copper islands on the Mosfet board and then you won't have to run this fourth wire.

The only part that's left now is LED1, which can be chassis-mounted to your box, with its anode connected to pin 4 of CON1 on the control board, and its cathode to pin 1. Make the three other connections from your Mosfet board to CON1 on the control board, as described above, and you are ready for testing.



The photo at left shows the original (hand made) prototype "Mosfet PCB" with its hand-cut breaks between the copper sections. Note how the gate pins here are all connected to (the red) insulated wire, not to the PCB. At right is the opposite side, with 8mm brass bolts soldered firmly in place, with heavy copper wires which pass through the board and are soldered to the top copper as well.



it will pull that pin down to 0V, which means that the voltage at pin 6 will always be higher than pin 7, so output pin 1 will go low, switching on Mosfets Q1-Q6. This switch is shown with dotted connections in Fig.1.

We've also shown the most convenient points to solder wires to go to the switch in Figs.2 & 3. Simply solder a wire here, to the COM terminal of an SPST switch, then a wire from the NO terminal of that switch to a convenient ground point.

When you activate this switch, you need to remember to switch it back into its normal position later, for the unit to go back to doing its job!

Case assembly

There are only four holes to drill: two in the lid for the battery terminals (main and auxiliary), plus one for the LED, and one 3mm hole in the side of the case for the ground eyelet.

If you're installing the optional bypass switch (S1), then you may wish to mount it on the lid, in which case you will need to drill an extra hole. Make sure that the switch won't foul the Mosfet board once it's mounted.

You will probably find that you have more room if you mount it low on the side of the case, and that may also make it harder to trigger the bypass function accidentally.

If you're using a metal case, ground is connected to the case internally and then externally, to the vehicle chassis or one of the battery terminals. You will also need to find a way insulate the two 8mm bolts from the lid of the case.

With a plastic case, the easiest way to provide a GND terminal is to feed a long M3 screw through the GND terminal on the Mosfet board, attaching it to the PCB in a similar manner as the two large 8mm screws (ie, with shakeproof washers and nuts). This can then project up through a fourth hole in the lid.

Or you could connect the ground eyelet to a screw which is externally accessible elsewhere.

There's no need to provide any insulation for the 8mm screws when using a plastic case; however, you will need to seal all the exit holes with neutral cure clear silicone, to ensure that the case remains watertight.

Download the panel label artwork from the SILICON CHIP website and print it at actual size. You can then cut it out and use it to mark out the hole positions in the lid. Drill them all to 3mm, then enlarge the two battery terminal holes to 8mm with larger drills, a stepped drill bit or a tapered reamer.

Laminate the label and cut out the holes using a sharp hobby knife. You can then stick it to the lid using contact adhesive or a thin smear of neutral-cure silicone.

Other options for creating adhesive panel labels are described on our website at **siliconchip.com.au/Help/FrontPanels**

Now plug the two boards together and join them using Nylon tapped spacers and machine screws. Mount the whole assembly on the underside of the lid, remembering to use insulators for the 8mm screw shafts if the lid is metal.

Attach the assembly to the lid using a flat washer and nut, then another flat washer and nut, which can later be used to clamp the battery wires or terminals.

Seal any possible water entry points (eg, around the LED lens) with neutral cure silicone, then, if using a metal case, drill a hole in the side of the case for the ground eyelet and attach it using a machine screw, shakeproof washer and two nuts.

You can then insert the sealing gasket into the channel in the underside of the lid, cutting it to size so that it fits around the full circumference.

With that in place, lower the lid onto the case and attach it using the supplied screws.

Don't forget to attach the case (if metal) or ground screw to the vehicle's ground, either via the chassis or to one of the battery negative terminals.

You can then wire up the two battery positive wires to the unit and verify that LED1 lights and the auxiliary battery begins to charge when you switch on the engine.

Don't forget to use heavy automotive cable with a sufficiently high current rating (25A+) to handle the high charging currents which can occur. The prototype used 35mm^2 automotive starter motor cable. SC

Parts list – Solid State Dual Battery Isolator

1 double-sided PCB coded 05106191, 98 x 71mm
1 double-sided PCB **with 2oz copper**, coded 05106192, 98 x 71mm
1 IP65 diecast aluminium box, 115 x 90 x 55mm [Jaycar HB5042/HB5044, Altronics H0423] ***OR***
1 IP65 polycarbonate box, 115 x 90 x 55mm [Jaycar HB6216/HB6217]
1 panel label, 115 x 90mm
2 35mm long M8 brass screws
6 M8 brass hex nuts
6 8mm ID brass flat washers
4 8mm ID brass or beryllium copper star/crinkle washers
4 8mm ID Nylon screw insulators (if using a metal case)
4 12mm long M3 tapped Nylon spacers
8 M3 x 6mm panhead machine screws
2 small eyelet quick connectors
1 M3 x 10mm panhead machine screw, shakeproof washer and two hex nuts

Semiconductors
1 LM339 quad comparator, DIP-14 (IC1)
1 LP2950ACZ-5.0 5V low-dropout linear regulator, TO-92 (REG1)
6 40V 100A+ N-channel Mosfets, TO-263-7 (Q1-Q6) [eg Infineon IRFS7434TRL7PP*]
1 5mm LED (LED1)
2 15V 1W zener diodes (ZD1,ZD2)
2 5kW 15-18V transient voltage suppressors, DO-214AB/SMC (TVS1,TVS2) [eg, Bourns 5.0SMDJ15CA-H*]
4 1N4148 small signal diodes (D1-D4)
1 5-pin SIL socket (CON1)
1 5-pin header (CON2)

Capacitors
1 4.7µF 50V electrolytic
4 100nF 50V ceramic or MKT
1 3.3nF 50V ceramic or MKT

** available from Mouser or Digi-Key*

Resistors (all 1/4W 1% metal film)
1 22kΩ 3 10kΩ 2 6.8kΩ# 3 4.7kΩ#
1 2.7kΩ 1 1.5kΩ 2 100Ω
use ±0.1% tolerance resistors for the tighter threshold ranges mentioned in the text

MAKING PCBS

Most of our projects use printed circuit boards (PCBs) because they make assembly so much easier and dramatically reduce the possibility of making mistakes. But PCBs are no longer available for our older designs, which may still be valid. And besides, you might want to make your own PCB for something you've designed yourself, or a modified version of one of our designs. Here's everything you need to know to go about doing that!

How handy would it be to be able to design and make your own PCBs in a short time frame? It could be that you need something a bit tidier or more compact (and reliable) than a breadboard.

Or maybe you're even considering commercialising your design. There's just something satisfying about seeing your design made real in fibreglass and copper.

We reviewed Altium's free CircuitMaker software in the January 2019 issue (siliconchip.com.au/Article/11378), which can be used to design PCBs.

We'll refer to such EDA (electronic design automation) software in this article, but our primary intention is to explain what happens after you have completed a PCB design.

by Tim Blythman

As well as covering the commercial manufacturing services and traditional etching methods, there are a growing number of alternative techniques being described to make PCBs, especially with the rise of consumer and hobbyist CNC systems such as 3D printers, laser cutters and mills.

And if you decide to take the commercial option, you may be surprised how reasonable the prices are, and the quality of the end result.

Why make a PCB?

You might still be wondering why you need to have a PCB made. There may be applications that you may not have considered for a custom PCB. As an example, take our April 2019 Flip-dot Display project (siliconchip.com.au/Article/11520), which uses small custom PCBs as mechanical elements.

That project also uses a PCB to form fifteen separate air-cored inductors from PCB tracks.

You can also use PCBs as shielding between circuitry running at significantly different potentials, as we did in our Versatile Trailing Edge Dimmer (February & March 2019; siliconchip.com.au/Series/332). And you can use PCBs as part or all of a case for a project, as we have done on many occasions; you can even use the copper layers for shielding.

It's also possible to get flexible PCBs made. The cost to get this done professionally is still daunting, but we'll cover more affordable hobbyist techniques for making flexible PCBs below.

Many PCB manufacturers can also create PCBs with aluminium cores, rather than fibreglass, which is used in high-dissipation devices, like radar systems and LED arrays. That's because aluminium conducts heat away from parts much better than fibreglass.

Anatomy of a PCB

We covered the anatomy of a two-layer PCB in our CircuitMaker article, but it's also possible to get four-layer (or more) PCBs made at a reasonable price. Here, we'll explain a bit more about how commercial operators make PCBs, and how this changes with the numbers of layers.

Whether the design has two or more layers, the early stages are not too dissimilar to the home etching process you might have tried. It starts with a sheet of fibreglass (the most common type is called FR4) clad on both sides with copper. A resist layer is applied to match the desired copper pattern, and the board is 'etched' by removing the exposed copper with a chemical that dissolves copper not covered by resist.

The board is then drilled (and any slots to be plated are routed), but this is about where the similarity ends.

A process for plating copper into the holes is used to create vias (which connect to the copper on both sides) and other plated-through holes. Then, an insulating solder mask layer is printed onto both sides of the board, followed by the silkscreen layer, which may be on one or both sides. The exposed copper is then coated with a protective layer of solder, or possibly silver or gold plating.

Finally, the boards are 'depanelised' (ie, cut apart). Typically, several different designs (or copies of the same design) are processed at the same time on a large panel for efficiency (24in x 24in [610mm x 610m] is a typical panel size), so they need to be separated.

This is usually done by a CNC routing machine, which can also rout slots and other shapes within the individual boards too.

For a four-layer PCB, the inner layers are etched as for a two-layer board, using a thinner core than the final product. The outer layers of copper are then laminated to the core using 'pre-preg', which is actually uncured fibreglass laminated with copper foil.

The outer layers of the PCB are then etched. The later steps proceed as for a two-layer board.

The four-layer technique can be extended to more layers as necessary, and there are variations where two or more two-layer boards can be sandwiched to give a similar result.

In any case, to make a board, especially one with many layers, we need information about what each layer will look like.

For a typical two-layer board, this amounts to six layers worth of information: two copper layers, two solder mask layers and two silkscreen layers (each pair is for the top and bottom).

There also needs to be information about the final board shape and the size and location of the drill holes and slots, making for a total of eight files. All this information is typically exported from your EDA program of choice.

On top of this will be information such as how thick the finished board will be and what thickness of copper is used. Other features such as silkscreen and solder mask colour can often be specified too. These specifications are usually made in a separate step, though.

File formats

Practically all PCB manufacturers will accept so-called 'Gerber' files for the manufacture of PCB designs. It is also called RS-274X.

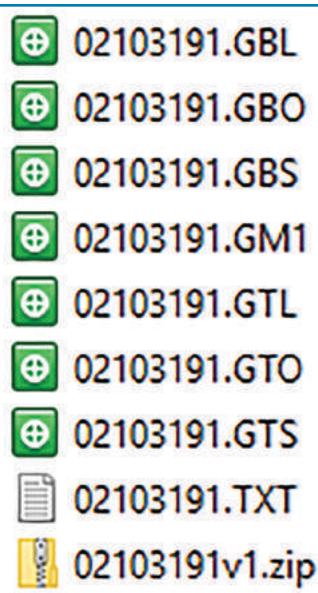


Fig.1: the eight Gerber files typically required to manufacture a double-sided PCB. In order, they are: bottom layer copper, bottom overlay (silkscreen), bottom solder mask apertures, board outline/routing, top layer copper, top overlay (silkscreen), top solder mask apertures, drilled holes and slots, and the zip package which contains the above.

A single PCB design results in not one, but rather multiple Gerber files, usually packaged in a .zip archive. We've emphasised the importance of the layers because, in the standard Gerber format, each layer is described by a separate file. The file extension of each file dictates what role it has. Fig.1 shows a typical set of Gerber files describing a single PCB.

From top to bottom, the layer names refer to the bottom copper, bottom overlay (silkscreen), bottom solder mask, mechanical (board outline) layer, top copper layer, top overlay, top solder mask and drill file. The .zip file describing the board simply contains these eight files.

The drill file is in a slightly different format to the other files, generally known as "Excellon" format; it is similar to Gerber but not identical. This is because the drill file was traditionally used to control a CNC drilling/routing machine, while the Gerber files were originally intended to be used with optical plotters that 'exposed' a light-sensitive resist layer.

The Excellon file instructs the machine to select a particular bit, then use that bit to drill at a series of locations, while the other files contain an assortment of shapes, such as rectangles and circles, which are combined to create the board pattern. These shapes are called 'apertures'.

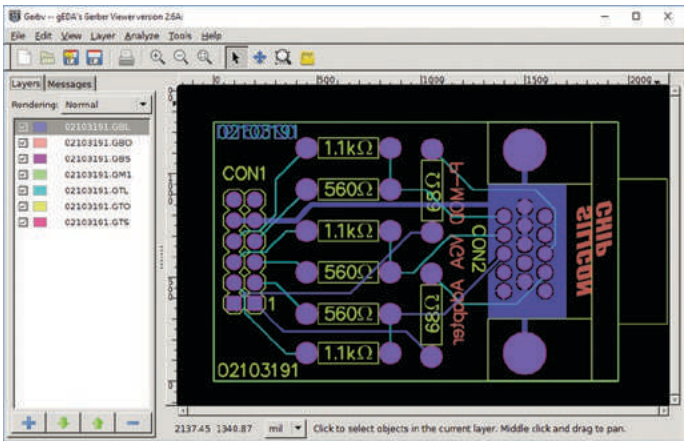
They literally were used as apertures for the optical plotters, but these days, the resist is applied differently and the Gerber files have simply become a standard way to describe the required patterns.

The Gerber files are now rendered by a computer, but the photochemical resist process survives, with the apertures replaced by a single computer-printed transparency.

The overlay and copper layers are rendered positively. That means that the Gerber file indicates where there should be copper or "silkscreen" ink.

The solder mask is rendered negatively, meaning the file dictates where there are holes in the solder mask. In other words, an empty copper file would result in no copper on the board, while an empty solder mask file would result in the board being covered in the solder mask.

The board outline layer is treated differently again. It consists of a series of lines or arcs which dictate the outline of the board. There may also



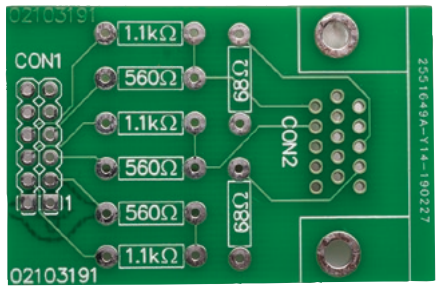


Fig.2: opening the files shown in Fig.1 in 'gerbv' produces this display. Colours are assigned randomly to each layer, for example, bottom layer copper is purple and top layer copper is cyan. Transparent rendering allows you to see all the layers in full, even where they overlap. The actual PCB produced by this file is shown at right.

be lines inside the board itself, which indicate the presence of slots (for example, for isolation) and other cutouts.

These lines are traced by a routing machine to give the board its final shape.

As this is done as the final step, any slots defined here will not be copper plated. If you need copper plated slots, eg, to solder flat component pins into, they are defined in the drill layer, using something known as a "G85" command. These are made before the through-plating process is applied.

It may seem odd that the drill file has a .TXT file extension, as if it is a text file, but Gerber and Excellon files are text-based; you can open any of these files in a text editor program like Notepad.

You will see a series of coordinates and commands, which will look familiar if you are used to working with CNC machinery.

The above is only a brief overview, but should give you an idea of what to expect when creating PCBs for your own use. We won't go into any detail about creating Gerber files; if you are using CircuitMaker, we explained how to generate Gerber files in the January 2019 article. Other EDA programs will have their own instructions on how to export Gerber files.

Just make sure that you provide all the required layers. In many cases, exporting the drill (Excellon) file is a separate step to producing the other Gerber files, so don't forget to do it!

And it's always a good idea to check the Gerber files before sending them off for manufacture, as it's quite common for some elements to be missing or extra elements to be present. We'll explain how to do that shortly.

Exporting PCBs as PDFs

You might have noticed that SILICON CHIP has historically published our PCBs as EPS or PDF files, a tradition that we continue to this day, although we now also offer commercially produced boards for virtually all of our published designs.

The main reason for doing this is that it's easy to print such files at home to produce a negative or positive mask that can be transferred to a resist mask for home etching. Both formats store and preserve dimensions, which is critical.

Some commercial manufacturers may be able to make a PCB from such files, but since they only describe the copper layers, you need Gerber files to have a proper board made with a solder mask, holes drilled to the correct sizes and so on.

These days, the PDFs we supply are mainly useful so that you clearly can see where tracks run on the board. Unless you really want to make boards yourself, the commercial boards are quite inexpensive considering the high quality

How to view Gerber files

We use the free open source program "gerbv" to check and validate our Gerber files.

It's available for Windows and Linux. The latest Windows version can be downloaded from **https://sourceforge.net/projects/gerbv/files/** and it is available as a system-installed software package for many Linux distributions (eg, "sudo apt-get install gerbv" in Debian-based distributions like Ubuntu).

As well as displaying Gerber files and allowing you to view and manipulate the layers, it also has the option of exporting to PDF, which is handy if you want to make PCBs using some of the more hobbyist oriented techniques.

But note that most versions of gerbv do a poor job of exporting to PDF when the PCB contains copper pours (large areas of copper which are not to be removed); these tend to get pixelated.

An up-and-coming version claims to solve this.

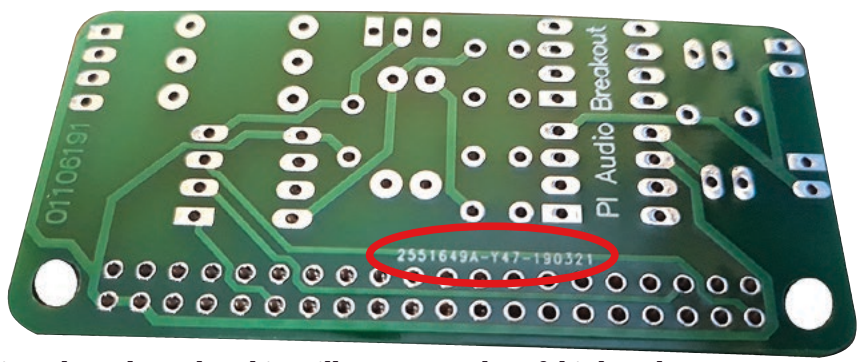


Fig.3: the code on the white 'silkscreen' overlay of this board (ringed in red), was added by the PCB manufacturer. It allows them to figure out to whom to send this PCB after it has been cut out of the large panel that was manufactured (known as "depanelisation"). Note how clean the tracks and pads are, and how accurately the holes have been drilled on this low-cost board.

If you have a 'zipped' set of Gerbers, you will need to extract the individual files before opening them in gerbv. Multiple layers can be opened from the File → Open Layer dialog box. You can change layer colours, rearrange and hide individual layers with the panel at left.

When exporting to PDF (File → Export → PDF), you can select one layer at a time by clearing all but one of the checkboxes in the layer tab. Change the layer colour to black by pressing F6 and picking the colour from the popup menu, if you plan to print the PDF as an optical mask.

You may need to set the background colour to make the layer visible; this can be done via View → Change background colour.

Fig.2 shows gerbv displaying the Gerber files for our recent (April 2019) iCEstick VGA Adaptor PCB (siliconchip.com.au/Article/11525).

The colours shown are assigned essentially randomly when you open up the layers and are designed to make each layer distinctive. You can change them to more realistic colours if you want (eg, green for copper, light grey for solder mask openings etc).

Getting PCBs made from Gerber files

The first technique for making PCBs is the one we use most at SILICON CHIP. It sounds really easy, too – we get someone else to do it!

In spite of what you might think, it's not expensive, and the results are very good.

Of course, the proviso is that you won't get the PCBs right away unless you pay a lot for "fast turnaround" and express delivery. It typically takes a week or two between ordering the PCBs and receiving them, sometimes longer.

So if you need a prototype today, you should probably look at one of the other options.

For smaller orders (eg, less than 100 units), the cost of manufacturing PCBs is normally kept reasonable by aggregating boards from many customers.

One minor side effect of this is that a small tracking code may be added to the silkscreen of your board, so that the manufacturer knows which board goes to whom.

An example of this is shown in Fig.3. It's usually quite small and placed in an out-of-the-way location.

Some manufacturers have web-based ordering while others accept files via e-mail and will send you a quote (usually within one business day). Ordering via e-mail can be convenient because this makes it easy for them to point out any problems they may find with your files so you can correct them before manufacturing begins.

Minimum quantities are usually in the order of 5-10, with a decreasing per-board cost as you order more. For prototypes, you'll generally want to order a small quantity, but it's good to have a couple of spares in case you make a mistake during assembly, or find it necessary to modify the board.

Design rules

If you've just started out using an EDA tool like CircuitMaker, Eagle, KiCad or DipTrace, you may not be familiar with design rules. They are an important part of PCB manufacturing since they aim to ensure that the design does not incorporate any elements which can not be easily and reliably made.

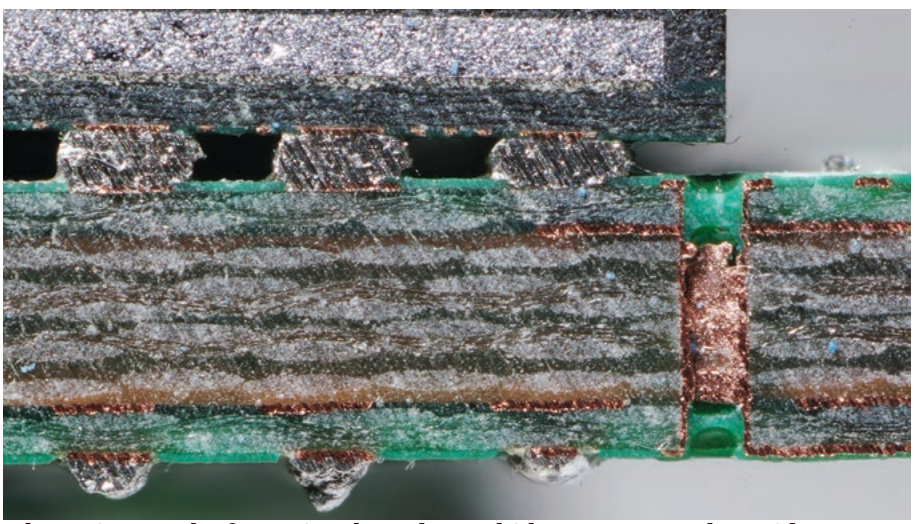
Board manufacturers generally supply a set of design rules which, if adhered to, guarantee that your design can be manufactured using their processes and equipment, with a minimal chance of failures. You can add your own, stricter design rules to ensure the safety of your design (such as ensuring separation between high-voltage tracks).

For example, you can see PCBCart's rules at www.pcbcart.com/pcb-fab/standard-pcb.html, partially reproduced in Fig.4.

In some cases, you can violate some

Board Size	Min 6*6mm | Max 600*700mm
Board size tolerance	±0.1mm - ±0.3mm
Board Thickness	0.4mm - 3.2mm
Board Thickness Tolerance	±0.1mm - ±10%
Copper Weight	0.5oz - 6.0oz
Inner Layer Copper Weight	0.5oz - 2.0oz
Copper Thickness Tolerance	+0μm +20μm
Min Tracing/Spacing	3mil/3mil
Solder Mask Sides	As per the file
Solder Mask Color	Green, White, Blue, Black, Red, Yellow
Silkscreen Sides	As per the file
Silkscreen Color	White, Blue, Black, Red, Yellow
Surface Finish	HASL - Hot Air Solder Leveling Lead Free HASL - RoHS ENIG - Electroless Nickle/Immersion Gold - RoHS ENEPIG - Electroless Nickel Electroless Palladium Immersion Gold - RoHS Immersion Silver - RoHS Immersion Tin - RoHS OSP -Organic Solderability Preservatives - RoHS
Min Annular Ring	3mil
Min Drilling Hole Diameter	6mil, 4mil-laser drill
Min Width of Cutout (NPTH)	0.8mm
NPTH Hole Size Tolerance	±.002" (±0.05mm)
Min Width of Slot Hole (PTH)	0.6mm
PTH Hole Size Tolerance	±.003" (±0.08mm) - ±4mil
Surface/Hole Plating Thickness	20μm - 30μm
SM Tolerance (LPI)	.003" (0.075mm)
Aspect Ratio	1.10 (hole size: board thickness)
Test	10V - 250V, flying probe or testing fixture
Impedance tolerance	±5% - ±10%
SMD Pitch	0.2mm(8mil)
BGA Pitch	0.2mm(8mil)

Fig.4: PCBcart's specifications and requirements. You will need to make sure your design adheres to these rules shown here, or they will complain when you send them your files. Luckily, all the rules can be programmed into the Design Rule Check settings of most ECAD software, and the software will then automatically inform you of any problems (or may not even allow you to create them in the first place!).



Photomicrograph of a section through a multi-layer PCB complete with an IC soldered to the top layer. The copper section at right is a via which connects two of the internal layers.

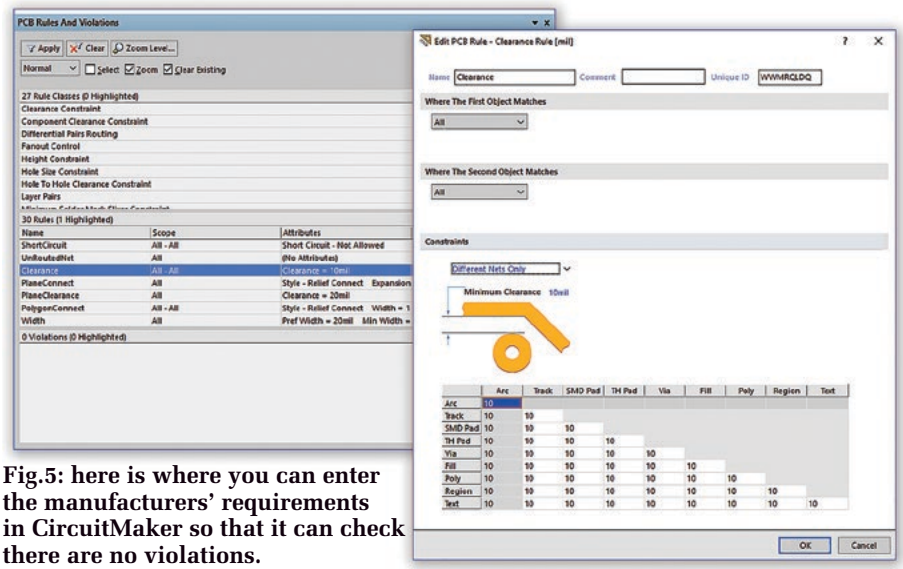


Fig.5: here is where you can enter the manufacturers' requirements in CircuitMaker so that it can check there are no violations. For example, the Clearance rule is set to 10mil in all cases, so it will ensure that there is a minimum of 0.01in (0.254mm) between adjacent conductors. Generally, you only need to make a few small changes to the default rules to suit typical manufacturers.

of the manufacturers' design rules slightly if you are willing to accept a higher percentage of faulty boards. Or they may charge you extra for the more involved processes required to manufacture your boards correctly.

Before we look at actual specs, let's get a "trap for young players" out of the way! Track thickness and track gaps are generally specified in "mils". A mil is not an abbreviation for millimetre! 1mil equals one thousandth of an inch, so a track width specified as 12mil will be 12 thousandths of an inch wide – about 0.3mm. Many people have been caught over the years – now you shouldn't be!

Most EDA software will naturally work in mils, although some have the ability to work to other standards. A tip: stick with mils, because that's what PCB manufacturers are expecting.

A typical rule is that copper tracks should be no less than 6mil (six thousandths of an inch or around 0.15mm) wide and no less than 6mil apart. Another common rule is that the drilled holes should be no less than 12mil in diameter (0.3mm).

If you were to place tracks 5mil (0.13mm) apart, they might still make your board, but you may find that some boards have short circuits between adjacent tracks. Or they may just reject it.

You should ideally set up the design rules before starting to lay out your PCB, although, as a general guide, if your board is easily hand-solderable and you aren't after any special board finishes or colours, virtually any manufacturer should be able to make your board.

Since most manufacturers have similar rules, once you have set them up, you should be able to have your board made by many different companies, perhaps with some slight tweaking to suit the stricter ones.

Most EDA programs offer automatic design rule checking, so it's worth entering the manufacturers' rules into your EDA program. It will then alert you to any violations, so you can fix them. Some PCB manufacturers offer downloadable design rule files that can be imported into your EDA program directly.

CircuitMaker's design rules can be accessed from the "View → Rules and Violations" menu, which opens the dialog shown in Fig.5. The minimum width and clearance constraints correspond to the trace width and separation noted above. Our choice of 10mil should be achievable by most board manufacturers (see panel!).

Order process

As mentioned above, some manufacturers take orders via e-mail. So, for example, if you want to order some boards from Sydney-based LD Electronics, e-mail your zipped Gerber

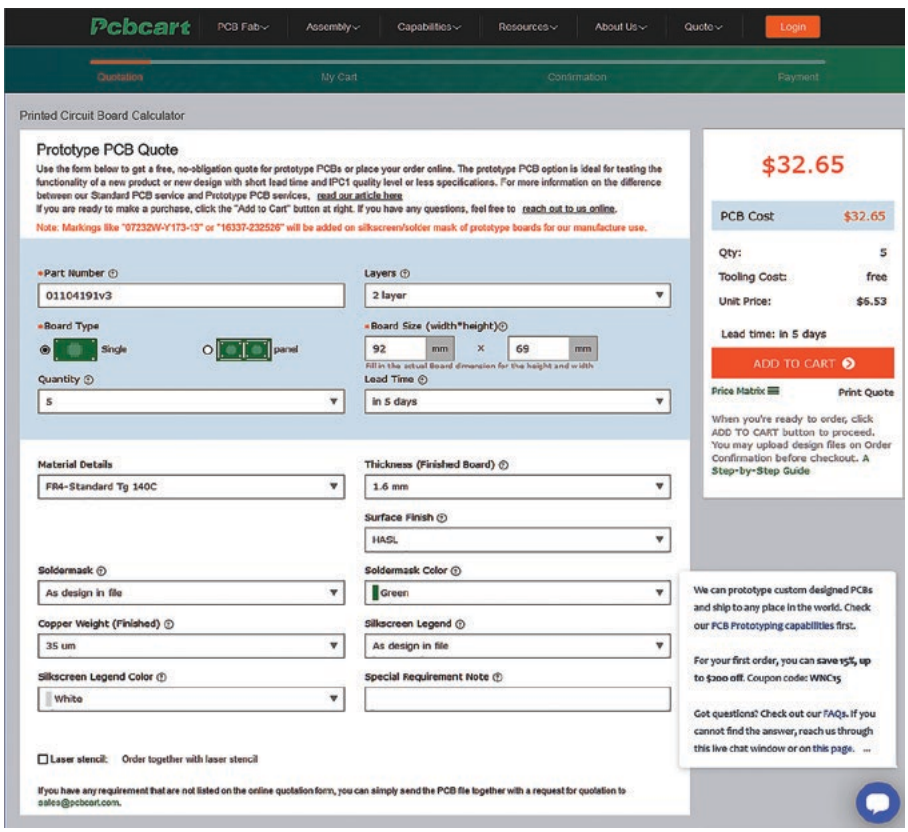


Fig.6: like many PCB manufacturers, PCBCart gives you an instant quote once you have put in your PCB's particulars. You can then log in, add the design to your cart, upload the Gerber files, fill in your details (eg, delivery address) and pay for the order. They'll start manufacturing your PCBs once your order has been submitted and will normally send you updates, and eventually a courier tracking number, via e-mail.

files to quote@LDElectronics.com.au along with any special requirements (board thickness, copper thickness, solder mask colour etc) and they will e-mail you back a quote.

They will then guide you through the order process.

On the other hand, as the name suggests, Guangdong, China-based PCBCart offers web ordering. You can get an instant quote by visiting www.pcbcart.com/quote and entering your requirements. Fig.6 shows this page.

We have already filled in the details of one of our boards, and you can see that the price (in US dollars) is being displayed at upper right.

We can then change the board quantity and other requirements and the price is updated.

The only fields that you need to fill in are those shown with an orange asterisk: the Part Number, Board Type and Board Size. The other defaults are fine unless you know you need something different. You can try changing some of the parameters and see how much non-standard features add to the cost of the basic PCB.

If you increase the quantity, you will see that the price doesn't go up all that much. In our example, five boards cost US$32.65 ($6.53 each) while 10 boards cost US$42.20 ($4.22 each) and 100 boards cost $213 ($2.13 each). This is typical, as there is a fixed cost associated with every different PCB made; making more copies of the same board has a lower incremental cost.

You can vary the board thickness between 0.4mm and 2.0mm; the cost varies slightly as you do this. 1.6mm is a typical thickness and a good default. 35µm copper is also known as '1oz' and is the default for single or double-layer boards; 70µm copper is '2oz' and costs a little more.

A green solder mask is usually the cheapest. In this case, there are other colours available at the same price (eg, blue and red) while other options increase the cost slightly. So does opting for a lead-free or gold finish, or a shorter lead time.

Note that a 30mil (0.75mm) wide track on a 35µm (1oz) copper board can handle 1A with only a 10°C temperature rise, so unless you have a specific high current application, thicker copper is usually unnecessary.

With the higher cost of 2oz copper, it's generally worth using wider tracks instead, if possible.

Like most online PCB manufacturers, PCBCart accepts payment by PayPal, including Visa or Mastercard. They offer delivery via DHL, UPS or FedEx. Other companies may offer cheaper options such as registered post. If you order from a local manufacturer like LD Electronics, postage will probably be quite a bit faster too!

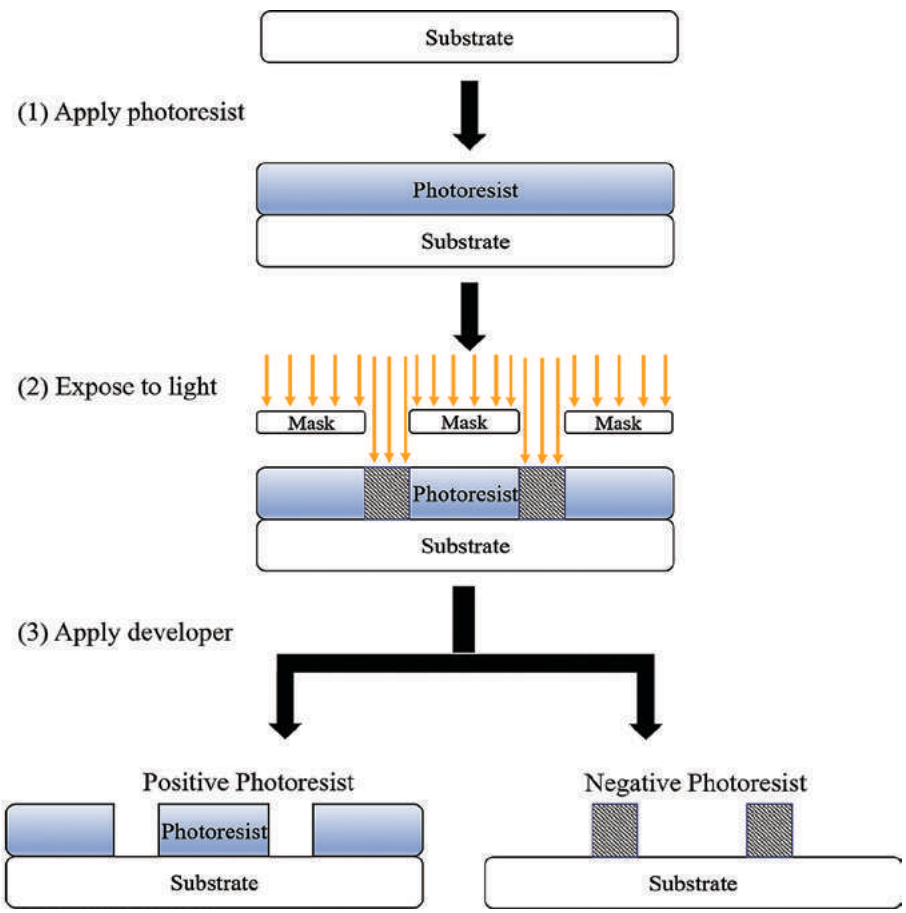


Fig.7: here's how the photochemical etch-resist process is used to produce a PCB (eg, using "Press 'n' Peel" film). Both positive and negative processes are shown.

RCS Radio's Ron Bell and his 31-thou limit

Older Silicon Chip readers would no doubt remember the name RCS Radio, if not its owner, Ron Bell.

If not the first manufacturer, RCS Radio was certainly a pioneer in this country, manufacturing "Printed Wiring Boards" for the military, industry and for the hobbyist from a factory in Canterubury (boy, were there some arguments when people started calling them that American name: printed circuit boards!)

But mostly we remember Ron "doing his nana" when patterns were sent to him with less than a 31mil track width or spacing. In fact, he'd get upset at anything under about 40-50mil!

This was long, long before computer software to produce PCB files. There weren't even computers in those days!

PCB patterns were hand-drawn with pen and ink; later this was superseded by black crepe tapes and pads.

Often, the patterns were produced at 200% scale, so that when reduced photographically, minor errors in drafting were also reduced. They didn't eliminate errors in the trackwork itself, though!

After Ron Bell's passing, RCS Radio was run by Bob Barnes, until his passing about ten years ago. By then, many production houses around the world were turning out PCBs which Ron Bell would have dismissed as "impossible!"

Doing it yourself

Of course, if time is of the essence, then ordering boards from China will not be your first choice. The age-honoured technique of etching copper from a pre-laminated board is still widely used, although modern methods put some twists on how the etch resist is applied.

There are also other techniques

available for removing copper, and it's now even possible to print a PCB using conductive ink, allowing the wiring to be 'drawn' directly onto a substrate. That really is a *printed circuit* board!

PCB etching

You might not think that PCB etching has changed much over time; indeed, the basic chemical technology is very much established and is still the primary method of commercial PCB manufacturers.

What has changed is the generation of the etch-resist layer, with some clever people using novel techniques.

If you have etched your own boards, you will have heard of ammonium persulphate and ferric chloride. But many board manufacturers use cupric chloride (green in solution) to etch their boards instead.

When cupric chloride ($CuCl_2$) reacts with copper, it turns into cuprous chloride (CuCl). These two compounds both contain only copper and chlorine, the difference being the 'oxidation state' of the copper atoms.

The beauty of this method is that the cuprous chloride (CuCl) can be turned back into cupric chloride ($CuCl_2$) by an oxidising agent.

This oxidising agent can be something as simple as oxygen from the air we breathe.

Of course, the chemistry is not that simple, and there needs to be a supply of chlorine atoms to supplement the copper atoms that are being added, although this can come in the form of hydrochloric acid.

The result is an etchant that not only doesn't get used up; it becomes self-generating.

There are downsides, of course. Cupric chloride is nasty stuff, and is worse for the environment than ferric chloride if released, which makes it difficult for hobbyists to use, particularly if the amount of cupric chloride keeps increasing.

That said, the actual etching works similarly to that of ferric chloride, with agitation and heat accelerating the process.

Ammonium persulphate is similar, but has the advantage that it doesn't stain anywhere near as much as ferric chloride. It has been said that if you walk within five metres of a ferric chloride bath, it will jump the gap and stain your clothes. A slight exaggeration perhaps, but . . .

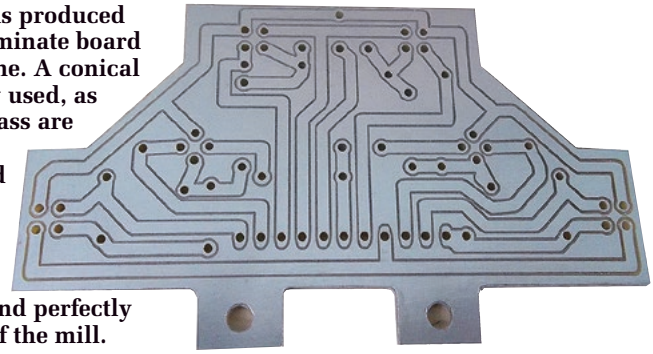


Fig.8: a PCB which was produced from a bare copper laminate board using a milling machine. A conical milling bit is normally used, as the copper and fibreglass are fairly tough and you want to cut a V-shaped groove. The main difficulty in doing a job as good as this is ensuring that the PCB is perfectly flat, and perfectly aligned with the bed of the mill.

Toner transfer etch-resist process

If you have access to a laser printer, toner transfer is one of the best etch-resist methods for a hobbyist.

While some toner transfer kits can be expensive, cheaper versions are available online. They aren't as good, but they can be made to work.

A PCB design is printed onto the glossy side of the toner transfer paper using a laser printer. It must be mirrored, as the transfer process mirrors the design a second time, so it ends up the right way around. The toner itself becomes the resist layer.

For this to work, the copper clad board must be spotlessly clean. Even fingerprints can impede the etching process.

The toner transfer paper is pressed against the copper cladding, and heat is applied. This can come from a clothes iron or even a laminating machine, although it appears some laminators can't reach the temperatures needed to transfer the toner.

After the board cools, the toner transfer paper is carefully peeled back, leaving the toner attached to the copper clad board, which can then be etched.

The copper under the toner will remain intact, as long as it isn't left in the etchant too long.

You can also use this method to produce a 'silkscreen' layer by applying the toner to a pre-etched board.

Incidentally, we've used the "toner transfer" method to produce a PCB using ordinary bond paper (ie, from a photocopier or laser printer). It takes quite a few attempts to get it right and importantly, the track spacing and gaps cannot be very fine. But it does work fairly well and is a great method for the hobbyist to try. (See **siliconchip.com.au/Article/6884**).

Photochemical resist processes

This involves a chemical which reacts to light, where the areas exposed

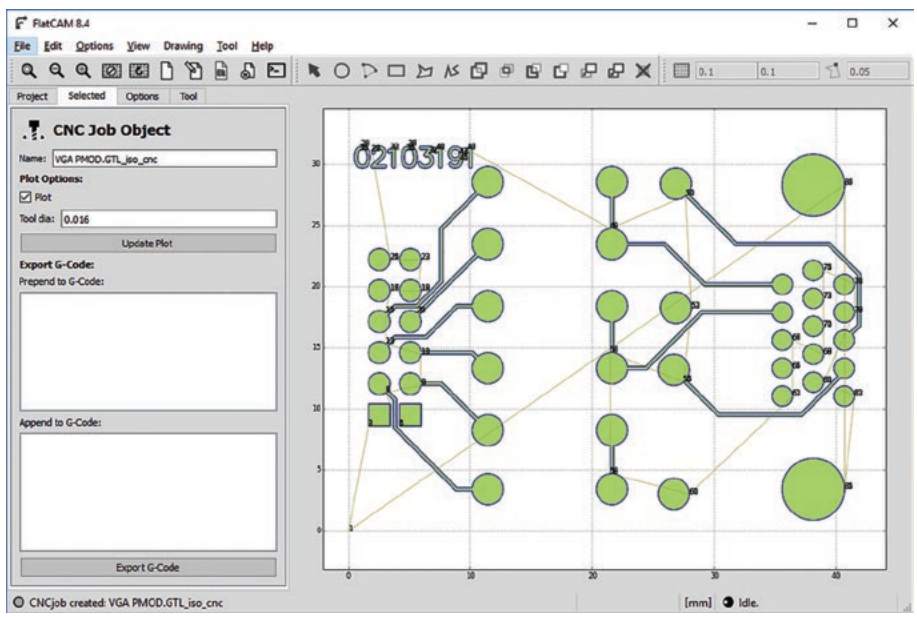


Fig.9: a screen grab of the FlatCam software which can convert Gerber files into G-code which can then be fed to a milling machine, laser cutter or other CNC equipment.

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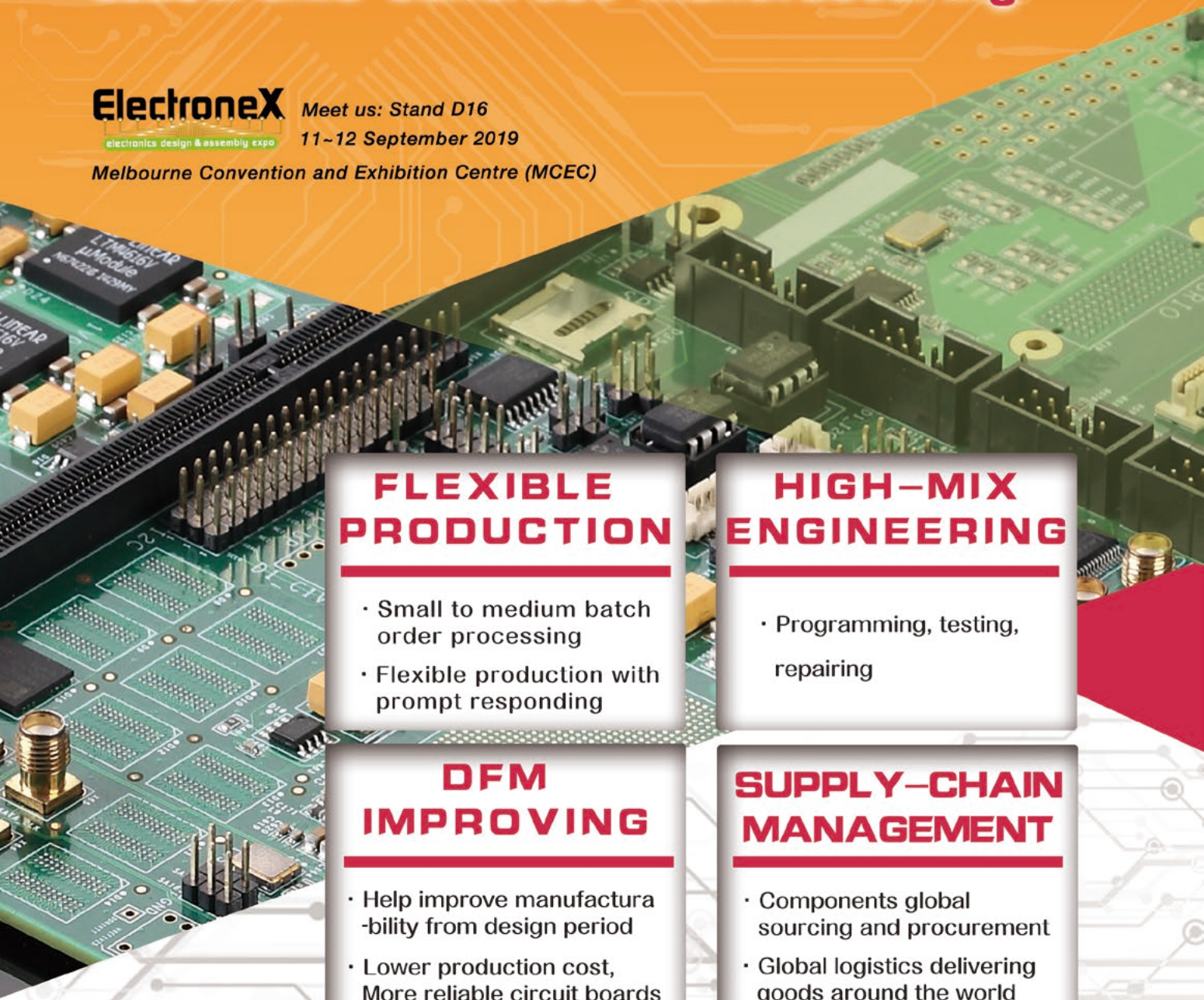

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to light change in chemical composition, allowing the unwanted parts of the layer to be chemically removed, leaving just the areas required to protect the copper underneath during the etching process.

You usually print the copper pattern as a mask on transparency film, then place that mask on top of the photochemical layer, which is attached to the copper laminate. You then expose it to UV light, either using a light box or by exposing it to sunlight.

The resist layer is then treated in a developing solution to remove the undesired parts of the resist mask, after which the board is etched as it would be for other resist types.

This is fairly close to the method used in factories for PCB manufacturing. It is vital to ensure that the resist layer is not exposed to light unnecessarily, as this lessens the effectiveness of the process.

Options for using a photochemical resist include both pre-sensitised boards, films that can be laminated to copper and even liquid photo-resist that can be painted onto copper-clad fibreglass. There are also options for negative and positive resists.

A negative resist is one that hardens where exposed to light, so the remaining etch resist layer corresponds to clear spaces in the transparency; the final PCB result is the negative of what is printed onto the film.

With a positive resist, the areas which are exposed to light are the areas which are then removed, and the areas which were not exposed remain to resist the etchant. Both options are shown in Fig.7.

Again, there are variations on this theme where a pattern printed onto plain (bond) paper is used to expose the PCB photoresist. It is important that the PCB pattern is in contact with the resist (ie, it is printed "wrong reading") so light scatter within the paper is minimised.

Fairly obviously, exposure times are rather significantly longer than when using transparency film.

Etch resist pens

Etch resist pens are typically used to touch up or repair the resist layer already applied to a board, where it has not transferred or printed correctly. They are also sometimes used to quickly sketch a very small PCB design by hand.

But they can also be used as part a CAM (computer aided manufacture) process. This involves the use of FlatCam (http://flatcam.org/) and a 3D printer.

Rather than using FlatCam to mill an isolation path, it can also be used to trace a resist path using a pen. The etch resist pen is attached to the head of the 3D printer, and it is commanded to lay down a resist path by the G-code that FlatCam generates.

It's a marvellously simple method, as it doesn't require any permanent changes to your 3D printer; the pen can be held in place with a rubber band.

The difficulty is in converting the Gerber files to an appropriate set of commands to drive the 3D printer. The best option we found is to use gerbv to convert the Gerber file to .png graphics, followed by using the http://svg-2stl.com/ website to convert these to an .stl file.

The .stl file can then be converted by any 3D 'slicer' program to files that can be printed on a 3D printer. You need a custom 'slicing' profile for the pen, so it can be lifted when moving between points; many programs offer a 'lift between extrudes' option, which is suitable.

By the way, most etch-resist pens work much better if the board is 'baked' before etching, to cure the resist layer. This is also true of many other methods, especially photo resist.

Filament extrusion

We've also seen a similar method but without even needing the pen; a 3D printer can be used to extrude plastic filament onto a blank copper PCB, with the filament forming the etch-resist layer.

Flexible filament appears to be the best choice. This helps to prevent the plastic from lifting off the PCB during the etching process.

Printing conductive material

If you have access to a 3D printer, you can also consider directly printing wiring using a conductive filament. But note that conductive filaments are not as good conductors as copper, so this method is mainly for low-power applications.

It's also pretty much impossible to tin the conductive filament; you need to melt the component leads into the filament. We're not sure how permanent the result is!

A typical 3D printer nozzle width of 0.4mm corresponds to a minimum track width of 16mil, so this method isn't capable of producing the fine details of other methods, and small SMD footprints will be impossible.

But it appears that having a 3D printer can still be a useful tool for making PCBs.

Voltera V-One PCB Printer

An extreme example of this is the Voltera V-One PCB Printer, which can not only produce double-sided PCBs up to 127 x 104mm using proprietary

Fig.10: the Voltera V-One can "print" a double-sided PCB up to 127 x 104mm. It's an expensive way to produce a board but when time is money . . .

conductive inks, but can also apply solder paste and perform reflow of populated boards.

You can see a video of the Voltera V-One in action at: **http://youtu.be/PeW1nURJ5ww**

According to the Voltera website, a complete, unpopulated board can be ready in around 35 minutes. Compared to a manufactured board, the Voltera PCBs will lack a solder mask and silkscreen layer, and the conductive ink is not as durable as bonded copper traces.

But the Voltera V-One is not limited to fibreglass substrates, and flexible substrates or even glass can be used.

The current listed price is US$4199 for the machine itself, with the cost of producing each board at around US$5 each.

If speed is of the essence and price is not a problem, the V-One is certainly worth checking out.

Milling PCBs

To form tracks on pre-laminated board, rather than etching, copper can be removed by mechanical means. Open-source and do-it-yourself CNC (computer numeric control) machines such as desktop mills, as well as similar commercial devices, can be used for this purpose.

A PCB mill routes insulating grooves in the copper layer to separate the copper into the tracks and islands required to form a circuit, as shown in Fig.8.

The same machine may be able to drill holes for the insertion of vias and through-hole parts.

While such a technique does not inherently provide the option for silkscreen labelling or solder masks, the grooves formed by the routing action makes it harder for the solder to form accidental bridges and production can be very fast, taking just minutes for smaller designs.

Double-sided boards are possible with accurate enough registration, although plated holes and vias must be created manually. Small copper rivets are available specifically for creating vias in such boards (they can also be used to repair commercially manufactured boards).

While it is possible to completely remove all unneeded areas of copper from a PCB using a mill, it is usually unnecessary, wasting time and wearing the milling bits. So PCB mills generally remove just enough copper to provide the isolation necessary for correct circuit operation, and no more.

An extra step is also needed if the copper needs to be tinned, although this is generally not necessary for a prototype board; tinning prevents surface corrosion, but if the board is assembled right away, that's less of a problem.

Another consideration for this technique is the waste produced, ie, copper and fibreglass dust. These are health hazards, especially glass dust, so a vacuum system is needed to keep this under control.

Suitable off-the-shelf PCB mills are available; the Bantam Tools Desktop PCB Milling Machine is an example of this. It is available from Core Electronics.

See: **https://core-electronics.com.au/bantam-tools-desktop-pcb-milling-machine.html**

Many people are also attempting to build their own PCB mills, some even using 3D printers with their extruder heads replaced by a rotary bit. The lateral forces caused by the milling bit moving through the material are much higher than would be experienced during 3D printing, so not all 3D print-

If you really *do* want to make your own PCBs . .

In this article, we've briefly mentioned methods of producing one-off PCBs yourself – perhaps from a magazine project or indeed a prototype for a new product.

And while we usually take advantage of today's low cost, speed and quality of commercial PCBs (which is why we've given up making them ourselves!) there may well be a time when you want a PCB *right now*!

Silicon Chip has published quite a few articles over the years detailing methods of making one-off PCBs, using a variety of production processes. We'll briefly recap on the most recent articles so if you really want to make a PCB yourself, you should be able to do so.

February 2001: Toner Transfer, by Heath Young. This article showed how you can "transfer" the toner from a pattern reproduced on bond paper from a standard laser printer to the blank board You then use that toner as a resist for etching. The difficult part is to carefully remove the paper, which you do by breaking it down, rubbing it under running water.

We've tried it, with mixed results, although we've proved it can be done.

Be prepared for a few misses before you get the system to work!

March 2001: Making photo-resist boards at home, by Ross Tester. We followed the last article with a more "traditional" approach using commercial resist-coated boards and exposing them to special UV lights (or the Sun, which is very high in UV!) through PCB patterns which had printed on a photo copier onto either transparent or semi-transparent film.

This is a time-honored method and is capable of very good results with fine tracks and spacing.

Incidentally, you don't have to buy pre-coated board – you can still buy blank board and photo resist, in either a liquid or spray-on form, or even as film which you can apply to the board. It's certainly not as common as it used to be but it is available (Google is your friend!).

February, 2012: Homebrew PCB via Toner Transfer Film, by Alex Sum. This uses a special film called "Press'n'Peel" which still available from Jaycar (HG9980). You print your pattern onto this film via a laser printer and use a hot laminator (or even a hot iron) to transfer the pattern to the PCB then etch, drill and cut in the normal way.

The author even used Press'n'Peel to create a component image on the top side of the board (similar to the silkscreen found on virtually all commercial boards).

ers are suitable for this conversion.

There are some challenges to milling PCBs. To get good results, the PCB must be very flat and level, as the milling depth will vary if the PCB is not entirely flat. Some mills can compensate for this.

Software for milling PCBs

Appropriate software is also required to convert Gerber files to a language that a 3D printer understands; typically G-code.

G-code is a slightly different subset of RS-274 than that used in Gerber files and is commonly used in CNC applications.

We found two programs which can do this, but since we don't have a mill, we couldn't test them fully.

FlatCam, mentioned earlier, is a very flexible and powerful program, and it can do the Gerber to G-code conversion that is needed to create a PCB using a mill – see Fig.9.

Another suitable program is pcb-2gcode, found at: **https://github.com/pcb2gcode/pcb2gcode**

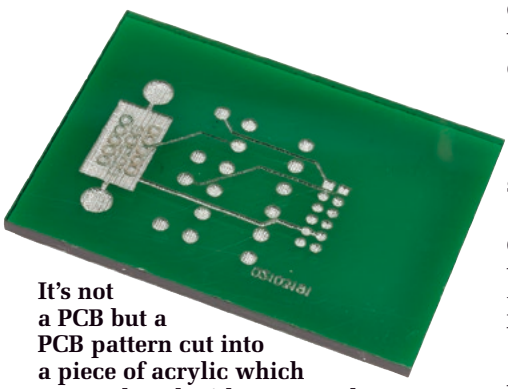
This has a much simpler command-line interface, although a graphical version is available.

Making PCBs with a laser cutter

There are a couple of different approaches to creating PCBs with a laser cutter. One uses the laser to react with a photochemical resist layer. Rather than using a mask, the resist is directly cured by a pass of the laser. It appears that the software to do this is straightforward.

We used gerbv to export a PCB layer in Gerber format as a PNG image, then imported this file into our laser cutting software. We then cut a scrap of acrylic as a test. The results can be seen in the photo below.

Because many CNC laser cutters are used to do engraving, the software is almost always capable of importing image files like this. Despite how easy it is to do this, we would be dubious to recommend it without further research into the specific chemicals being used and how they might react to being hit by laser radiation.



It's not a PCB but a PCB pattern cut into a piece of acrylic which we produced with our CNC laser cutter – just to prove it could be done!

That's why we tried it on a piece of perspex and not a PCB.

For example, it's well known that vinyl should not be cut in a laser cutter as it releases toxic, corrosive chlorine gas which will poison you and damage your laser cutter. Any compound that contains chlorine will have a similar result.

Also, you will have to tune the speed and laser intensity to get a good result, and in doing so, if the laser power is too high or cutting speed too low, you could cut through the etch-resist layer, with unknown consequences.

Another variation we've seen, which may be more practical, is to coat the copper clad board with black paint and using the laser to blast it away to match the negative of the PCB pattern.

The remaining paint forms the etch-resist mask, and the board is etched. In this case, the development step is not needed.

If you have an industrial power laser cutter, it may even be possible to simply vaporise copper off the board, producing PCBs in a single step. Drilled holes could also be completed by having the laser linger a little longer!

In brief, a laser cutter could make a great tool for producing PCBs, but we have our doubts as to the safety of the process, both for human and machine.

Printing circuits on other substrates

We mentioned that the Voltera V-One PCB Printer can print on glass or even flexible substrates. PCB manufacturers can also create aluminium-core or flexible PCBs at a price.

We'll mention some techniques we have seen which allow hobbyists to create their own PCBs with unusual substrates.

Just as it is possible to buy copper clad fibreglass panels (blank PCBs), so too is it possible to buy copped clad polyimide (DuPont calls this "Kapton") in sheets, ie, blank flexible PCBs.

The copper clad polyimide sometimes goes by the name "Pyralux". Polyimide is hardy stuff and can handle the harsh conditions of an etch bath.

The substrate lends itself well to the toner transfer resist method, but we have seen some people comment that the Pyralux tends to curl when exposed to heat; for example in a heated etch bath.

The curling may cause the etch resist to lift. We suggest fixing the sheets to a rigid backing during the etch process to prevent this.

This method could also be used to create custom flexible flat cables (FFCs).

It's also possible to buy sheets of copper foil, in which case there is no limitation on what substrates are possible, as long as there is a way to bond the two together.

We have seen home-made kevlar PCBs, where the copper is bonded to the kevlar using fibreglass resin. It seems the secret here is clamping the two together rigidly to ensure that the surface to be etched remains flat.

We've even seen PCBs made on glass using a similar technique, although soldering onto such a board would be quite fraught; you would have to do it carefully to avoid breaking the glass from differential heating – possibly by directly heating the glass itself.

Conclusion

In this article, we have presented an assortment of PCB manufacturing techniques that are accessible to the hobbyist, but we haven't been able to mention every possible variation.

The rise of home CNC type machines such as mills, laser cutters and 3D printers is making it possible to do many things that we would not have dreamed of previously. Some techniques are still being developed and improved, including the traditional ones.

Having a laser cutter at our disposal tempts us to try some of the methods we have mentioned above. However, we will have to do further research to ensure we do not damage our machine or risk our health.

If we needed to make a prototype board today, we would use the toner transfer or a pre-sensitised photochemical board, followed by a bath in ferric chloride or ammonium persulphate.

And when we're in less of a hurry, we order commercial prototype boards. That is, until someone lends us a Voltera V-One . . . SC

PRODUCT SHOWCASE

Fully-automated PCB prototyping

Electronics developers prefer to create their printed circuit boards directly in the laboratory. This is fast and easy with the new circuit board plotters from LPKF Laser & Electronics AG. Whether the all-rounder LPKF ProtoMat S64 or the special system for HF applications, LPKF ProtoMat S104; the fully-automated machines guarantee the production of fine structures to 100µm.

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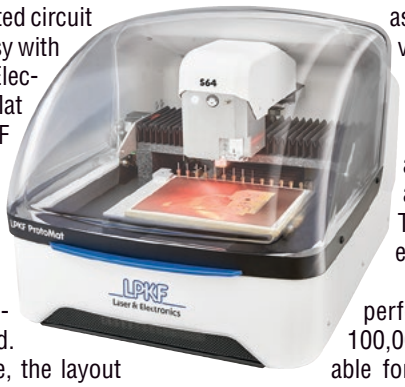

For the etch-free process, neither special knowledge nor special laboratory equipment is required. Thanks to digital control via easy-to-use software, the layout can be flexibly adapted at any time. The user has control of every process step, the ideas remain in-house and no coordination with external service providers is necessary.

The LPKF ProtoMat S64 is the reliable and fast working basic system for almost all in-house PCB prototyping applications. The high-speed milling spindle allows the production of structures up as small as 100µm. The included dispenser and vacuum table makes the LPKF ProtoMat S64 the perfect addition to any development environment.

The LPKF ProtoMat S104 sensor-controlled material and copper thickness measurements are carried out automatically and enable the exact determination of the required milling depth. The milling width adjustment also automatically ensures a constant width of the milling contours.

Thanks to the vacuum table and the high-performance spindle, which operates at up to 100,000 RPM, the LPKF ProtoMat S104 is also suitable for HF applications and thin laminates as well as substrates with sensitive surfaces.

The system software also takes into account the special requirements of RF materials.

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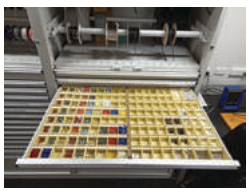

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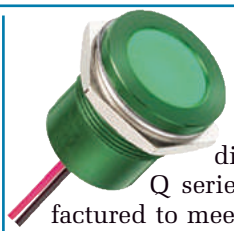

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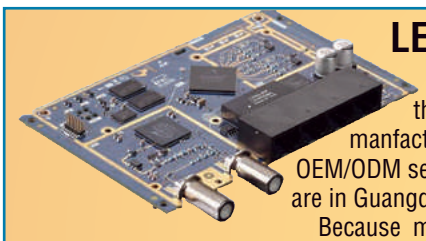

LEACH: from PCBs to finished product in one factory

In China, there are thousands of contract manfacturers providing PCBA/OEM/ODM services (most of them are in Guangdong province).

Because many factories focus on consumer products, they need huge quantities to keep their SMT lines running for 24 hours. The Chinese market has a large demand for consumer products.

But the risks are also high: so many companies develop very fast, then, disappear suddenly.

Regular Silicon Chip readers would recognise the name "LEACH", a China-based company who advertise regularly in the magazine.

LEACH was founded in 1999. It is not huge factory but has a total of three SMT lines, two through-hole lines and one box assembly line. Since they focus on industrial and commercial products, they accept any quantity of orders. Their work lines can switch a maximum of 25 types of boards per day.

With a stable and capable team of 88 employees, all multi-skilled, LEACH can purchase from global suppliers and deliver to the entire world.

LEACH focusses on industrial products and can accept high mix/low volume. They have engineers to help with lay-out/DFM and provide both full-turnkey serviceas well as partial-turnkey builds.

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Speech Synthesiser with the Raspberry Pi Zero

Most electronic devices communicate with us via blinking lights. But humans use speech to communicate virtually any concept easily and clearly. So wouldn't it be better if your electronic gadgets spoke to you? Now you can make them do just that, with a low-cost Raspberry Pi and our simple hardware and software, in just about any language. They can even play music!

We have published several projects over the years which can be used to play back sounds, and many of these can be (and have been) used to play back recorded voice samples to indicate to a user what is going on inside an electronic device.

But you're usually limited to just a handful of voice samples, restricting the information that you can convey with such devices.

Not so with this one, which can generate a virtually unlimited number of different phrases, short or long. They broadcast clearly, in the language of your choice, and with the option of several different accents.

You just need to feed in text over a serial port (eg, from just about any microcontroller or computer), and it will be translated into sound.

These days, pretty much every portable electronic device (and some which are intended to be placed around the home) can speak to its users.

We wanted to be able to add that capability to any microcontroller-based project in a compact and low-cost package, and that is what we have achieved.

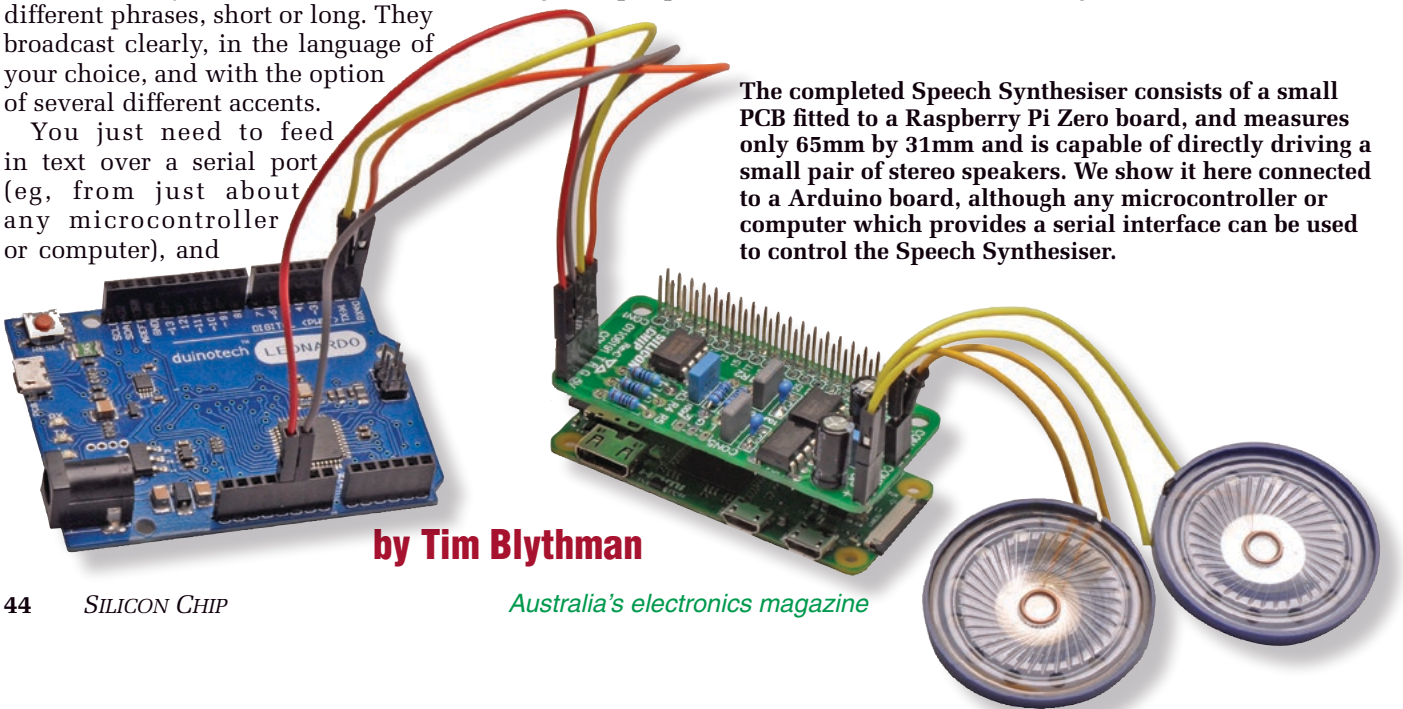
Various speech options

Single-chip 'speech solutions' do exist, such as the SpeakJet (www.magnevation.com/SpeakJet.swf).

While capable of generating speech and other sound effects, it still requires an external filter and amplifier.

The SpeakJet IC costs over $50, and while impressive in what it does for its size, we think our solution is competitive on cost and versatility, even if it is slightly larger.

We've also seen an Arduino speech shield, closer to $100 in cost, which is more expensive than our solution and also larger.



The completed Speech Synthesiser consists of a small PCB fitted to a Raspberry Pi Zero board, and measures only 65mm by 31mm and is capable of directly driving a small pair of stereo speakers. We show it here connected to a Arduino board, although any microcontroller or computer which provides a serial interface can be used to control the Speech Synthesiser.

by Tim Blythman

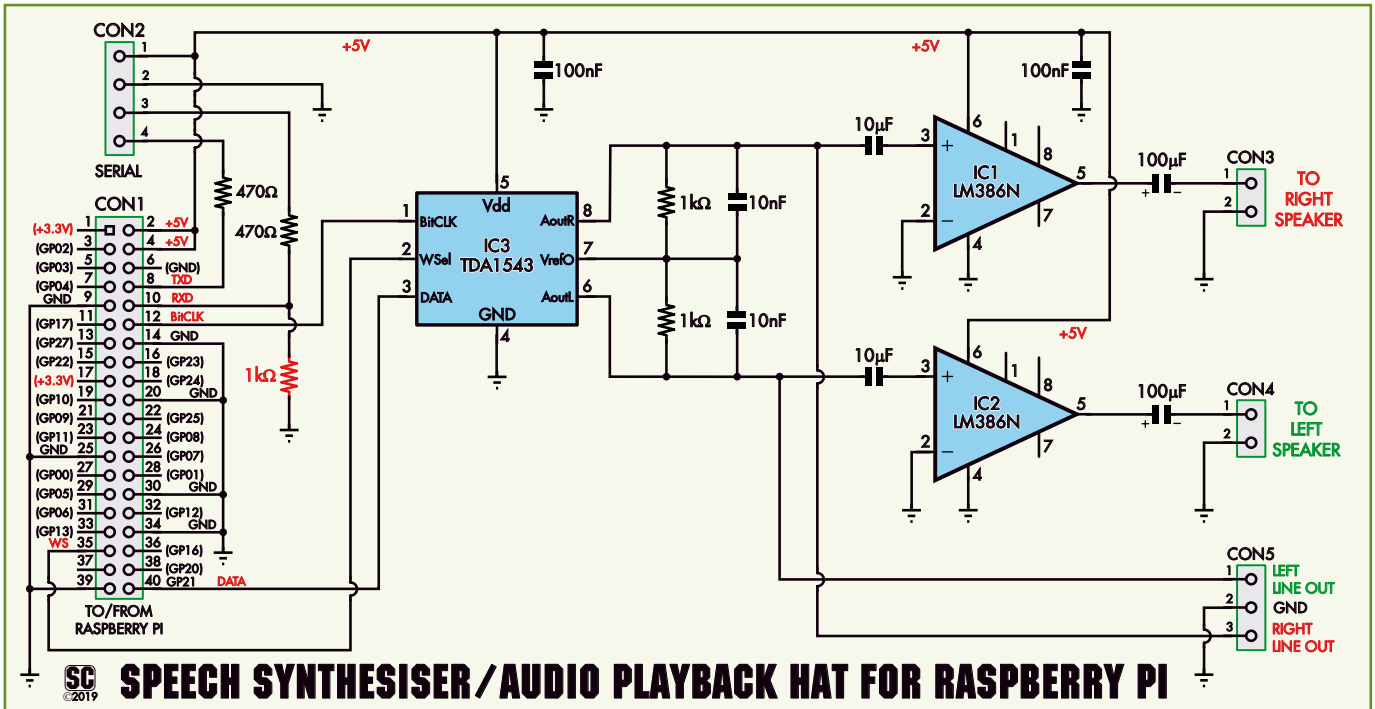


Fig.1: the circuit of the Raspberry Pi hat which adds the ability to drive two speakers. It can be used for speech synthesis or general audio playback. Audio data comes from the Pi via header socket CON1 in I²S digital format and is fed to DAC IC3. The analog audios signals are then coupled to amplifiers IC1 & IC2 and on to headers CON3 and CON4, which connect to the speaker(s). The resistor shown in red is left off for 3.3V signal levels on CON2.

Enter the Raspberry Pi Zero

These days, the Raspberry Pi 3B+ can be bought for around $60 plus postage from several resellers. But the Pi 3B+ is overkill for what we need.

So we've turned to a smaller relative, the Raspberry Pi Zero. Remarkably, the Raspberry Pi Zero can be had for under $10 from Core Electronics (https://core-electronics.com.au/raspberry-pi-zero.html).

It is actually a small form-factor variant of the earlier Raspberry Pi Model B. Of course, there is a catch, and the Raspberry Pi Foundation has limited sales of the Raspberry Pi Zero to one per customer.

The Raspberry Pi Zero also lacks features such as WiFi or even a headphone socket.

The Pi Zero W adds WiFi, but is still subject to the one per customer limit. We tried to buy a Pi Zero and a Pi Zero W at the same time and were not allowed.

There is also the Pi Zero WH, which adds WiFi and soldered headers to the mix. There are no limits on the sale of these, fortunately, although it does retail for around $20, or twice the cost of the basic Pi Zero. However, all of these choices are excellent value for money.

To turn our Pi Zero (of whatever flavour) into a Speech Synthesiser, we need to get audio out and amplify it, and for this, we've created a small DAC and amplifier board to provide direct stereo speaker drive.

Our DAC/amplifier board is the same shape as a Raspberry Pi Zero and sits directly above it. You'll also need some speakers and a microSD card to create a finished, working Speech Synthesiser, as well as some means of supplying serial commands to the completed unit, so it knows what to say.

Advanced users could even program the Raspberry Pi directly in a language such as Python, but you would need to be reasonably confident using a Linux command line. We have also provided some code to allow an Arduino board to control the Speech Synthesiser.

Why try Pi?

The Raspberry Pi series of single-board computers are astonishingly cheap for what they are, and this project would work with any current variant of the Raspberry Pi.

The larger models will result in a less compact finished product, but would provide a great way to experiment with speech synthesis before committing to buying another, smaller Pi.

The speech synthesis software we're using is an open-source project called "espeak-ng" (see https://github.com/espeak-ng/espeak-ng). It includes many different languages and voices, so it is perfect if you need speech in English or just about any other language.

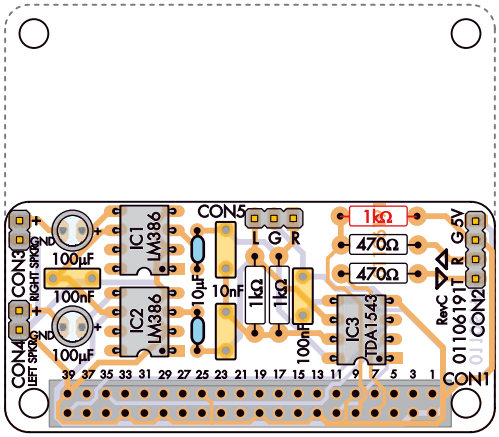
You can download variants of espeak-ng for different operating systems, such as Windows, if you would like to hear what it sounds like first. You can find these downloads at: https://github.com/espeak-ng/espeak-ng/releases

Since the Pi Zero is capable of running a wide range of advanced software, we've included some extra features in our Speech Synthesiser.

We've also included another open-source program, "madplay" (https://sourceforge.net/projects/mad/files/madplay/). It can decode and play MP3 files, so if you also want to use your Speech Synthesiser as a simple sound effects module, you can do that.

If you have one of the WiFi-enabled Pi variants, the Speech Synthesiser can also become a very simple internet radio. Instead of playing a file, madplay can decode and play an internet radio station using a single command.

We developed the software for this



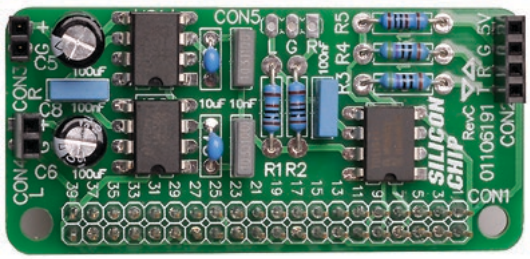


Fig.2: the Pi audio hat is quite compact and easy to build, with relatively few components. Take care with the orientation of the ICs and electrolytic capacitors. CON1 is mounted on the underside and plugs into the GPIO header on the Raspberry Pi host. CON2 is for serial communications. The resistor shown in red is left off for 3.3V signal levels on CON2. Speaker wires could be soldered directly to the board, rather than fitting headers CON3 & CON4. The dotted outline at left shows the size of the regular Raspberry Pi PCB, giving an idea of how the board would fit on one.

project using a Raspberry Pi WH, as the WiFi allowed us to download the necessary software packages directly from the internet.

This also lets us use SSH (secure shell) via WiFi to tweak our settings remotely.

So while the Pi Zero is the cheapest option, and requires the least power to operate, you do give up some interesting possibilities compared to the WiFi-enabled variants.

Hardware overview

The Speech Synthesiser consists of a few parts, primarily the Raspberry Pi itself plus a 'hat' that we have designed, which plugs into it and allows it to drive one or two speakers.

This is necessary as the Raspberry Pi Zero does not have any onboard analog audio outputs.

The circuit for this 'hat' is shown in Fig.1. It connects to the pin header of the Raspberry Pi via CON1, a 2x20 pin socket. CON2 is a 4-pin header which makes the 5V supply from the Raspberry Pi available (eg, to power an Arduino board or similar), plus a 2-wire serial interface for control.

The three resistors between CON2 and CON1 allow a 5V device like an Arduino to communicate with the Raspberry Pi's serial port, which operates at 3.3V.

If you will be controlling the Speech Synthesiser from a 3.3V micro board or similar, then you should replace the two 470Ω resistors with wire links (or fit them anyway, it won't matter) and omit the 1kΩ resistor to disable the voltage conversion.

This UART serial port is the primary means of control and communication between the external microcontroller and the Raspberry Pi microcomputer, which handles all the speech synthesis and audio playback tasks. IC3 is a TDA1543 16-bit digital-to-analog converter (DAC). It is fed digital audio data, in I^2S format, from the Raspberry Pi on pins 12, 35 and 40 of CON1. These are the bit clock, word clock and serial data pins respectively. Pins 6 and 8 of IC3 are the analog audio outputs, which act as current sinks.

The current flow is proportional to desired audio signal voltage levels for the two stereo channels.

These currents are converted into voltages by the two 1kΩ resistors connected between those pins and the voltage reference output, pin 7, which sits at around 2.2V and can supply up to 2.5mA.

The DAC switching artefacts are attenuated due to the filtering action of the 10nF capacitors across these resistors, and the resulting voltage signals are coupled to the non-inverting inputs of audio amplifiers IC1 and IC2 via 10µF non-polarised capacitors. IC1 and IC2 are LM386 amplifier ICs which need minimal external components.

Their 5V supply from the Raspberry Pi is bypassed by a shared 100nF capacitor. Their outputs are AC coupled to the speaker terminals, CON3 and CON4, by a pair of 100µF electrolytic capacitors which remove the DC bias in the signal. This is provided by IC1 and IC2, to keep the signals within their supply rails.

With pins 1 and 8 of IC1 and IC2 left open, each amplifier provides a voltage gain of 20 times.They can both deliver around 250mW into an 8Ω load.

The line level signals are fed separately to pin header CON5 in case you need to feed them elsewhere, but keep in mind that these signals are not ground-reference, but instead have a DC bias of around 1V.

Software

The software for this project can be downloaded from the SILICON CHIP website.

It is a large download, around 400MB. That's because the software is supplied as a complete installation of the Raspbian Lite operating system,

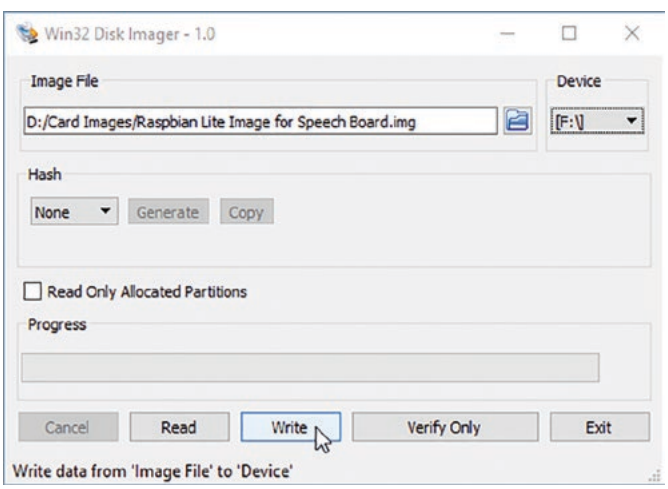
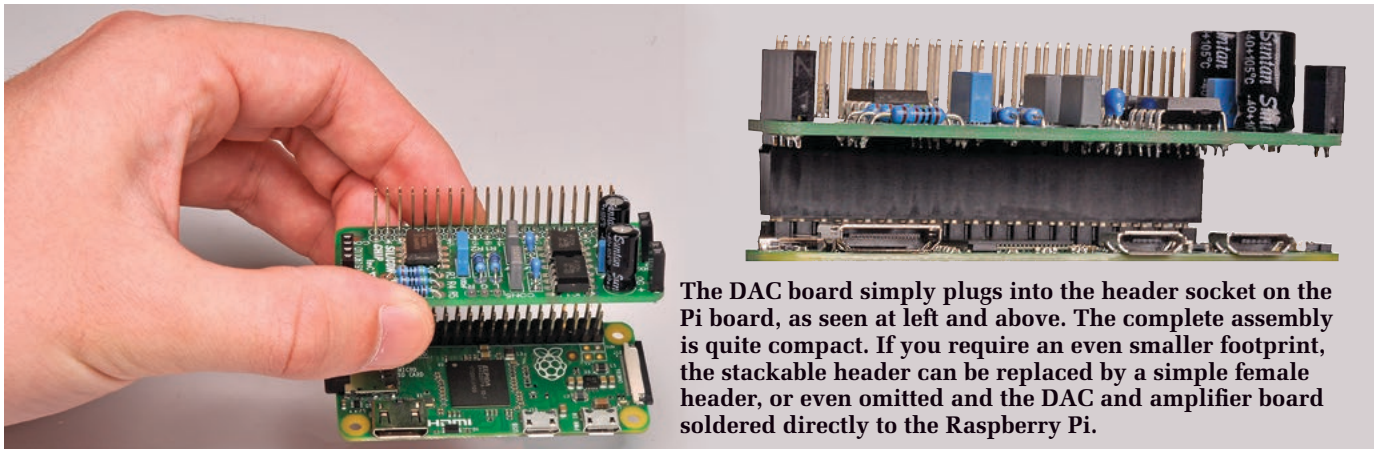


Fig.3: Win32diskimagewriter is a Windows program used to write the Pi software to the microSD card. You can start with our pre-configured image, or a basic Raspbian Lite installation if you are customising your software. Take great care using Win32 diskimagewriter as it can overwrite your data if used incorrectly.



The DAC board simply plugs into the header socket on the Pi board, as seen at left and above. The complete assembly is quite compact. If you require an even smaller footprint, the stackable header can be replaced by a simple female header, or even omitted and the DAC and amplifier board soldered directly to the Raspberry Pi.

with some extra packages and settings incorporated.

Raspbian Lite dispenses with the graphical user interface normally included with Raspian, reducing the install size (and therefore download size) substantially.

You can fit the software on a 2GB microSD card, although larger cards can be used. You can either write our supplied image directly to your card, or follow the instructions below to set up the operating system in a step-by-step fashion. The step-by-step method is more involved and requires a bit more knowledge of the Linux command line.

One disadvantage of using our 2GB image is that your file system will be limited to 2GB, even if you use a larger card, and much of the space is already taken up by the operating system.

If you need more than 2GB (eg, you want to store a large number of audio files on the card), then you should use the step-by-step process and a higher-capacity card.

The step-by-step approach is also best if you wish to customise your setup, but note that you will need a Raspberry Pi variant with WiFi to download the packages.

As noted above, we're using **espeak-ng** and **madplay** to provide the audio functions. We also need to apply some custom settings to enable the UART serial control interface and the I^2S (digital audio) interface. Plus, if you're using a WiFi-enabled variant, it's necessary to set up the WiFi interface.

We're also configuring the Pi to boot from the microSD card in a read-only mode.

This allows us to simply remove power when we're finished with the unit, rather than having to send a serial command to perform a 'clean shutdown', as would be necessary if the card was writeable during use.

This does not permanenly make the card read-only, as you can easily add a jumper to enable write access temporarily.

Building the DAC and amplifier board

The DAC/amplifier 'hat' board is a handy little device that can be fitted to any variant of the Raspberry Pi. Use the PCB overlay diagram, Fig.2, as a guide during construction.

Start by fitting the resistors. As mentioned earlier, leave out the 1kΩ resistor at upper-right if you will be controlling the Raspberry Pi from a microcontroller that has 3.3V I/O levels.

Follow with the ICs, which can either be soldered directly to the board or plugged into sockets. Regardless, ensure they are orientated correctly, with their pin 1 indicators towards the bottom of the board as shown in Fig.2.

Next are the MKT and ceramic capacitors, which are not polarised, then the electrolytic capacitors, which are. Their longer leads indicate the positive end and this must face towards the right side of the board, as shown by the + signs on the overlay diagram and PCB itself.

The stripe on the capacitor cans indicates the negative end and so should face away from the + signs.

Finally, fit the pin headers, with the 2x20 pin socket mounted on the underside of the board as shown. You might like to plug it into the Raspberry Pi board before soldering it, to ensure it sits correctly.

You could use a stackable header here, which would be useful if you plan to connect any of the other Raspberry Pi I/O or supply pins to external circuitry (other than the serial port, which is already wired to CON2 for you).

Alternatively, you could dispense with CON1 entirely and solder the hat directly to the Pi. But if you do this, take care that the underside of the DAC and amplifier board does not touch the top of the Pi. You may like to slide a strip of plastic or insulating card between the two to ensure separation.

Keep in mind that you will need access to the microSD card slot. 5V DC power can be fed to the Pi through CON2 if necessary.

Similarly, you could solder wires directly to the speakers rather than fit headers for CON3 and CON4. Once the board is complete, plug it into the Raspberry Pi, and you are ready to install the software.

Simple software setup

The simplest way to set up the software for the Speech Synthesiser is to download our firmware image. This is a .img file which has been put into a .zip archive to make it smaller. The .img file is a byte for byte 'snapshot' of the SD card.

Unfortunately, that means it's not possible to do a simple copy and paste, as the file needs to overwrite everything including the existing file system on the card.

So we need to use a program called Win32diskimagewriter to write the image to the SD card. Win32diskimagewriter is written to work on Windows computers and can be downloaded from **siliconchip.com.au/link/aaps**

If you have a different operating system, then alternatives such as Etcher (**www.balena.io/etcher**) or the "dd"

Step-by-step software set-up procedure

This process is more involved than simply using the image file, as described in the main body of this article, but gives you a lot more options. We don't recommend doing this with a Raspberry Pi variant that lacks WiFi since that is a lot more fiddly. But you could set up the SD card on a Raspberry Pi equipped with WiFi and then plug it into a Pi Zero.

The first step involves writing a Raspbian Lite image to the card, which is practically the same process as we described for our custom image. These files are available for download from www.raspberrypi.org/downloads/raspbian/

We used the November 2018 version of Raspbian Lite.

Write the Raspbian Lite image to the card using Win32-diskimagewriter, Etcher or dd, as described in the text. Under Windows, there should be two drives created, one named "boot" and another that Windows cannot recognise. Windows will say that it wants to format the unrecognised partition, but do not let it!

The initial contents of the boot drive are as shown in Fig.6. Open this drive and find the file called "config.txt", then open it with a text editor such as Wordpad or Notepad++. Some versions of Notepad do not recognise the line endings that Linux uses, and may not display the file correctly, so we do not recommend that you use it.

Now scroll to the end of the file and make the four changes shown in Fig.7.

The first and third enable the I2S output, to send data to the

```
# Uncomment some or all of these to enable the optional hardware
interfaces
#dtparam=i2c_arm=on
dtparam=i2s=on
#dtparam=spi=on

# Uncomment this to enable the lirc-rpi module
#dtoverlay=lirc-rpi
dtoverlay=hifiberry-dac

# Additional overlays and parameters are documented
/boot/overlays/README

# Enable audio (loads snd_bcm2835)
#dtparam=audio=on

# Enable UART
enable_uart=1
```

Fig.7: we've made four changes to the "config.txt" file on our image, as shown here. These set up the Pi to send audio to our DAC and amplifier board, and to turn on the UART to enable serial communications.

DAC on the hat, and disable the default audio output (which is via the HDMI display connector). The second configures the I²S output to suit the DAC we are using. The fourth change allows the console to be accessed over the UART serial port.

If you want to make any more changes to this file, now is the time, as it will be easier to perform edits on a PC than on the Pi. Save the file when finished.

Now create a text file on the boot drive named 'wpa_supplicant.conf', and edit it to contain the following lines:

```
country=AU
ctrl_interface=DIR=/var/run/wpa_
  supplicant GROUP=netdev
update_config=1
network={

ssid="network"
psk="password"
key_mgmt=WPA-PS
}
```

Change the "country", "ssid" and "psk" values to match those of your own WiFi network, and then save the file.

If you think you might want to use SSH to access the Pi, create a file named "ssh" in the root of the boot drive. The file doesn't need to contain anything; it merely needs to exist. Now safely remove the microSD card from your PC and insert it into the Pi's microSD card slot. Connect it to your host microcontroller, or whatever you are using to communicate with the Pi over its UART serial port.

Power it up and open to the serial port on the Pi at 115,200 baud. After about five seconds, you should see the screen fill with boot messages. When the Pi connects to your WiFi network, a message showing its IP address can be seen; this is handy if you wish to use SSH for further communication.

After around a minute, you will see the login prompt, as shown in Fig.8.

The default username is "pi" and the default password is "raspberry". Enter these, and you will end up at the command prompt,

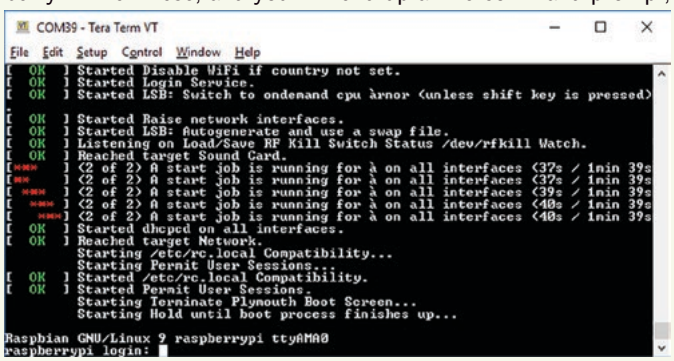

COM39 - Tera Term VT
File Edit Setup Control Window Help
[OK] Started Disable WiFi if country not set.
[OK] Started Login Service.
[OK] Started LSB: Switch to ondemand cpu kernor (unless shift key is pressed)
[OK] Started Raise network interfaces.
[OK] Started LSB: Autogenerate and use a swap file.
[OK] Listening on Load/Save RF Kill Switch Status /dev/rfkill Watch.
[OK] Reached target Sound Card.
[OK] (2 of 2) A start job is running for a on all interfaces (37s / 1min 39s
[OK] (2 of 2) A start job is running for a on all interfaces (37s / 1min 39s
[OK] (2 of 2) A start job is running for a on all interfaces (39s / 1min 39s
[OK] (2 of 2) A start job is running for a on all interfaces (40s / 1min 39s
[OK] (2 of 2) A start job is running for a on all interfaces (40s / 1min 39s
[OK] Started dhcpcd on all interfaces.
[OK] Reached target Network.
Starting /etc/rc.local Compatibility...
Starting Permit User Sessions...
[OK] Started /etc/rc.local Compatibility.
[OK] Started Permit User Sessions.
Starting Terminate Plymouth Boot Screen...
Starting Hold until boot process finishes up...
Raspbian GNU/Linux 9 raspberrypi ttyAMA0
raspberrypi login:

Fig.8: if you can see the login prompt in your terminal window, the Pi is booting correctly, and serial communication is working.

from which we can continue to set up the Pi. Run the following command to update the package list, by typing the command and then pressing Enter. It may take a few minutes, or even longer:

```
sudo apt update
```

Then run:

```
sudo apt-get install espeak-ng raspi-gpio madplay
```

This installs the **espeak-ng**, **raspi-gpio** and **madplay** programs. You may be prompted during the install; press "y" and Enter to proceed. While the raspi-gpio program is not necessary for the Speech Synthesiser, it will be handy if you wish to use the Pi's other GPIO (general purpose input/output) pins. At this point, everything should be working sufficiently to allow the Speech Synthesiser to function. It can be tested by running this command at the prompt:

```
espeak-ng "testing"
```

You should hear the word "testing" coming through the speakers.

The next step is to set the microSD card to be read-only. Before you do this though, you may wish to install more programs or copy other files, as it will be easier now than later.

When we say we are setting the microSD card to be read-only, note

that this is only a software setting this is used by the Pi and does not affect whether or not it can be written by other systems. There also some utilities installed which allow the Pi to use a ramdisk overlay, for any programs that expect to be able to write to the disk.

If you wish to write files to the ramdisk for your own application, the easiest way is to create a file in the /tmp folder, which exists on the ramdisk. But note that its contents will be lost the next time the Pi is rebooted or powered down.

To set up the read-only SD card, run the command:

wget https://raw.githubusercontent.com/adafruit/Raspberry-Pi-Installer-Scripts/master/read-only-fs.sh

This downloads the required script. When the download completes successfully, run this command:

sudo bash read-only-fs.sh

This will provide several prompts to be answered before applying its settings.

There are options to set a GPIO pin as a jumper to GND, to allow write access (the jumper is only read at boot time and applies until the next reset). We suggest setting this to GPIO21, as it can easily be jumpered to GND by placing a jumper across two pins of the GPIO header.

This is actually one of the pins used for the I²S audio data, but the jumper only needs to be placed long enough to be detected at boot time, so will not interfere with the audio. Fig.9 shows the pin allocations for the Raspberry Pi header, including the suggested jumper location.

GPIO16 can be set to allow a jumper or external transistor to shut down the Pi. Both of these pins can be configured differently in the script. Just follow the prompts.

You can also choose to force the Pi to reboot on a kernel panic (ie, an unrecoverable operating system fault), which may be handy, although that is unlikely to happen.

Now that's all done, download and install some packages and apply the settings you have chosen. You can reboot after this by running the command:

sudo reboot

The software on the Pi has now been set up and is ready to use.

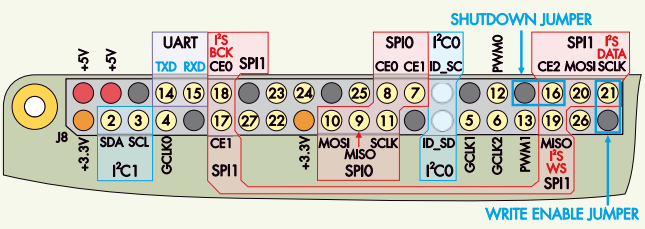


Fig.9: the pinout of the Raspberry Pi's 2x20 way header, with the functions used by our software shown in red (I²S audio data) and blue (serial transmit/receive), along with the recommended shutdown and write-enable jumper locations. If you fit a stackable header to the hat board, jumpers and other accessories can still be easily connected to the Pi.

Parts list (audio hat)

1 double-sided PCB coded 01106191, 65 x 31mm
1 2x20 way header socket (CON1)
  [Jaycar HM3228 or Altronics P5387 for stackable variant]
1 4-way header or socket (CON2) for connection to the host microcontroller
2 2-way male header (CON3, CON4)
  [optional, for speaker connections]
1 3-way male header (CON5) [optional, line out]

Semiconductors
2 LM386 audio amplifier ICs (IC1,IC2)
1 TDA1543 stereo DAC IC (IC3)
  [Silicon Chip Online Shop Cat SC3029]

Capacitors
2 100µF 10V electrolytic
2 10µF multi-layer ceramic [eg, Digi-key Cat 445-181284-ND]
2 100nF MKT or multi-layer ceramic
2 10nF MKT

Resistors (all 1/4W 1% metal film)
3 1kΩ 2 470Ω

Other parts for complete Speech Synthesiser
1 Raspberry Pi Zero, Zero W or Zero WH
  [eg, from Core Electronics]
1 power supply to suit Raspberry Pi
1 microSD card, 2-32GB
1 or 2 small 8Ω speakers [eg, Jaycar AS3004]
1 microcontroller board (eg, Arduino Leonardo)
4 jumper wires to connect a microcontroller to Speech Synthesiser board
Wire or jumper wires to connect speakers

command under Linux perform the same task. Other programs will have their own instructions for writing images to cards.

Connect the microSD card to your PC; if your computer does not have a card slot, use a USB card reader/writer (eg, Jaycar Cat XC4740 which costs a princely $5). Install Win32diskimagewriter and open it.

Extract the .img file from the .zip file and click on the folder icon under "Image File" to select the image file. Double check that the "Device" setting matches your microSD card.

Win32diskimagewriter is capable of writing to almost all sorts of media, so make sure that you aren't telling it to overwrite your USB stick or hard drive. This is very important!

Fig.3 shows an example of what the Win32diskimagewriter program looks like just before writing to the card. Finally, click "Write". This process may take ten minutes or even longer, depending on the speed of the card and other factors.

Once the write has completed successfully, remove the microSD card from your computer and insert it into the Raspberry Pi.

If you want to set up the software from scratch, refer to the panel at left with the step-by-step procedure.

Connecting to a host

To control the Pi and trigger speech synthesis and audio playback, you need a device which can communicate over

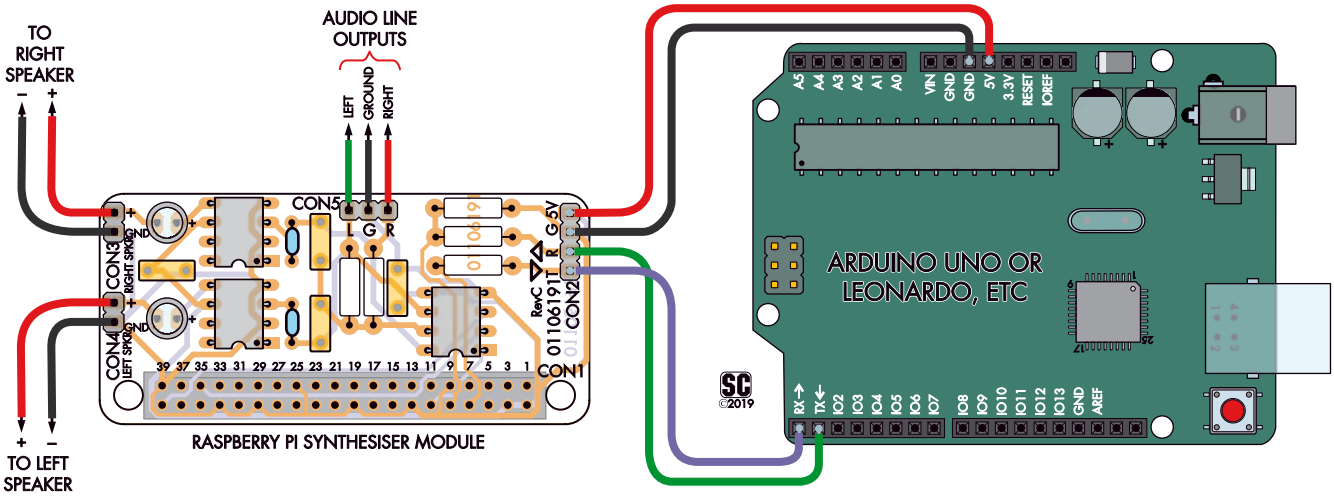


Fig.4: connect the Leonardo board to the Speech Synthesiser as shown, for testing or to develop your own Arduino code to drive the Synthesiser. Note that the Pi will draw a few hundred milliamps from the 5V supply, so ensure that it can get the power it needs or you may have glitches.

a serial UART interface. We used an Arduino Leonardo microcontroller board, as it has two serial ports; one is a virtual serial port connected to the USB interface while the other is a hardware-based serial port which is connected to a pair of accessible I/O pins.

Initially, we'll just use the Leonardo as an interface between your PC and the Raspberry Pi for testing purposes. Later, you can program the Leonardo to trigger speech and sounds by itself.

Start by programming the Leonardo with our "USB-Serial_for_Leonardo" sketch (also available for download from the Silicon Chip website).

This makes the Leonardo equivalent to a simple USB/serial converter. It won't work on Uno boards, as they only have one hardware serial port.

If you don't have a Leonardo, any other Arduino board based on the ATmega32U4 microcontroller should work. For example, you could use a small "Beetle" board, like the one we used for PC Remote Control Interface in the August 2018 issue (see siliconchip.com.au/Article/11196).

Connect the Leonardo as shown in Fig.4. This allows it to supply 5V to the Raspberry Pi board. While there will inevitably be a voltage drop across the jumper wires supplying current to the Pi, we did not find this to cause any problems.

If you do find you have power problems on the Pi, or noise in the audio, you may be able to solve this by powering the Pi directly using its own micro USB socket and an external USB plugpack.

In this case, don't connect the 5V supply wire. The Arduino board can still get its power from the computer.

Another option for the test procedure is to use a CP2102 USB/serial converter.

To do that, simply wire up the converter to CON2 on the hat, but note that you will need to leave out or remove the 1kΩ resistor at upper right as these devices operate with 3.3V signalling levels.

Terminal software

While it's possible to use the Arduino serial monitor to communicate with the Pi via the Arduino, other terminal programs such as PuTTY or TeraTerm have better terminal emulation support which suits the Raspberry Pi interface.

In particular, if you wish to do any file editing on the Pi (which may be necessary to enable specific settings), a proper terminal program is mandatory.

Regardless of which terminal software you use, you will need to connect to the Pi at 115,200 baud with eight bits and no parity (8-N-1).

Generating speech

If you have chosen the step-by-step setup, you will have already tested out the Speech Synthesiser. If you have installed the pre-configured card image, then you will want to see what the Speech Synthesiser is capable of before setting up your controller.

After the Pi has booted, you need to log in using the username "pi" and password "raspberry". Later, if you set up an Arduino (or another device) to control the Pi directly, you will need to program it to wait for the login prompt and then send these strings, followed by newline characters, so that it can log in automatically. Our sample software demonstrates how to do this

The espeak-ng program we're using for speech synthesis has a multitude of options, and a full list of command parameters can be listed by typing the command:

```
espeak-ng - - help
```

For example, using the voice parameter, we can apply a different accent. The parameters start with a dash and are usually listed before the text to be spoken.

For example, type:

```
espeak-ng -ven-us "testing"
```

You should then hear the word "testing" in an American accent. Or try:

```
espeak-ng -s 125 -v en+f5 "testing"
```

This will also say "testing" but in a female-sounding voice. Of course, you can modify the text inside the quotes to make it say different words and phrases.

There are currently no Australian or New Zealand accents available, but a clever choice of spelling can be used to emulate regional pronunciation.

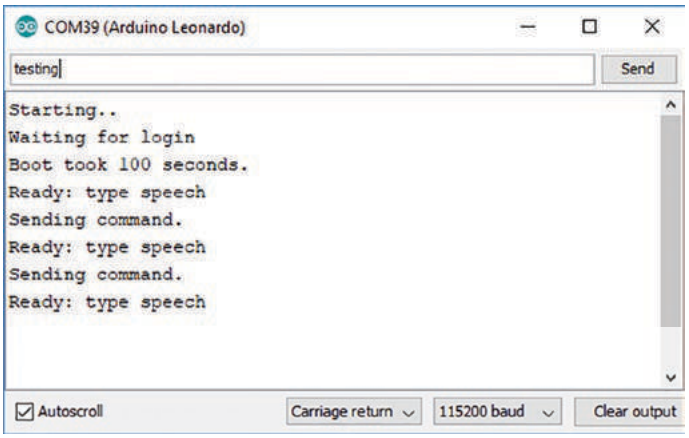


Fig.5 (above): our sample program logins into the Pi's console and then sends commands to speak whatever is typed into the serial monitor. When the "Ready: type speech" prompt appears, it is ready for speech synthesis.

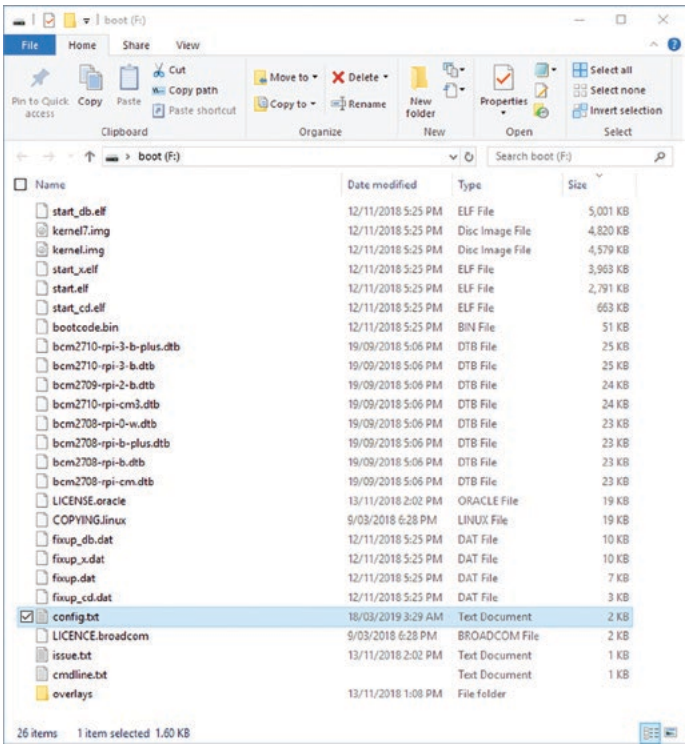


Fig.6 (right): some files on the microSD card for the Pi can be edited on a PC as the "boot" volume uses the common FAT file system. This is much easier to do than using the Pi's inbuilt text editor. The "config.txt" file contains many settings, including which services are started at boot time.

Other parameters such as reading speed, voice pitch and volume can also be adjusted similarly. See the output of the "help" command mentioned above.

Playing MP3 files and internet radio

As we noted earlier, you can also use "madplay" to play MP3s or internet radio streams. Using this software is straightforward.

For example, issuing the command:

```
madplay file.mp3
```

will play the "file.mp3" track, assuming it is located in the current directory of the Pi. If the file name has spaces or other special characters in it, put the name in quotes (single or double). You can issue this command:

```
madplay - -help
```

to list the command line parameters which madplay accepts.

To play an internet radio stream, you will need a version of the Pi with WiFi, and that WiFi needs to be configured to connect to the internet via your router.

For this task, we're combining two Linux commands: the aforementioned madplay, to play the audio, plus a package called "wget", which downloads the audio stream over the internet.

These are combined in a single command, with the content of the stream being piped by the wget command from its source URL to the input of madplay. The stream will continue unless there is an error, or it can be stopped early by pressing Ctrl-C. For example:

```
wget -O - "http://us5.internet-radio.com:8487/"
  | madplay -
```

It isn't always obvious what the URL is for the actual radio stream, as you're expected to use an online directory to find and play the streams.

We found it useful to visit www.internet-radio.com and then opening up each .m3u file in a text editor (eg, notepad) to determine each station's stream URL.

Putting this URL into the above command should then allow you to play that station using the Pi.

Controlling this all automatically

Our final goal was to be able to use the Arduino board to control the Speech Synthesiser and audio playback automatically. To this end, we've created a basic sample sketch which communicates with the Pi, including the login process.

Any text sent to the Arduino over the regular serial monitor is then sent to the Pi as a command, to be spoken.

Note though that if the Pi is still booting when you send the text, you will have to wait for it to finish before hearing it spoken.

The sample sketch is called "Pi_TTS_Interface" and is again available for download from our website. Upload this to the Leonardo board using the usual procedure and open a serial terminal or the serial monitor.

The sketch will report on its status and prompt for text to be spoken when ready. An example of the output of this sketch is shown in Fig.5.

You can use this sketch as a starting point for your own voice control schemes. As the cliche says: the sky is the limit!

What else can you do?

As a small computer in its own right, the Pi is capable of much more than what we've outlined here, especially the versions equipped with WiFi such as the Pi Zero W.

There's a lot of information available on the internet on how to program the Raspberry Pi, so if you're keen to make yours do more, head over to your favourite search engine and start investigating the possibilities. You'll learn a lot more by "doing" than by "reading!" SC

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25% OFF LED DRIVERS

TECH TIP: LED DRIVERS
Choose the right LED power driver to get the maximum efficiency from your LED lighting. High power LEDs require a constant current, this is to avoid over current and overheating. If installing LEDs outdoors or in a wet environment ensure you use LEDs with the right IP rating, generally IP64 or higher.
See our range of constant voltage or constant current LED power instore or online.

MW MEAN WELL

- 12/24V OPTION
- INDOOR USE
- IP42 RATED

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- INDOOR OR OUTDOOR USE
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NOW FROM **$22.45**
Suitable use for decorative lights, strip lights in kitchens, robes and bathrooms.
- Constant voltage
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Suitable use for lighting and moving sign applications i.e panel lights and downlights.
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- 1.8m SAA approved input lead & mains plug included

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NEW

JUST **$9.95**

Rechargeable Li-ion battery
Compatible with many older generation Nokia phones, portable speakers, and other rechargeable devices. BL-5C type. 3.7V 1020mAh. *Due early July.* SB2291

SEE MORE ON PAGE 2

USB POWERED

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Single-channel Li-ion / Ni-MH battery charger
Designed to charge a 3.7V rechargeable Li-ion battery or 1.2V AA, AAA Ni-MH/Ni-Cd battery. USB powered. MB3702

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Connect directly to your battery and power up to 5 devices. Large battery clips. Dual USB ports. Suits 12/24V batteries. PS2039

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Convert 24VDC to 12VDC so you can use normal car accessories designed for 12V vehicles. Dual USB ports. Built-in noise filter. MP3356

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half price!

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Outputs 12/16/19VDC @3.5A. Includes 10 plugs to power most laptops. 2.1A USB port. 6600mAh. MB3719 **WAS $39.95**

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10,000mAh portable powerbank
2.4A Fast charge. Dual USB. Micro USB charging lead included. **WAS $39.95ea.**
Black MB3795
White MB3796

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NEW

12V mini DC uninteruptible power supply

Keep your equipment running longer during a power outage. 2.5A output. DC power. Built-in rechargeable Li-ion battery. Integrated smart charger. 3 interchangeable DC connectors supplied. MP5240

TechTalk:

Lithium rechargeable batteries

Lithium battery technology has been around for many years and come in primary (one-time use) and secondary (rechargeable) types. The rechargeable Lithium battery family is collectively referred to as Lithium-ion (Li-ion). There are many different types of Li-ion rechargeable batteries, all use Lithium as the base cathode (negative terminal) material combined with another substance, and carbon for the anode (positive terminal). For example, a common type of Li-ion battery is the Lithium Iron Phosphate, referred to as LiFePO4, or Li-Po. The energy density of Li-ion batteries is much higher than other battery technologies, for instance a 1Kg Li-ion battery can store about 150WH, compared to 25WH for a lead-acid battery.

The cell voltage of Li-ion batteries is also higher than that of competing technologies, for example a Li-ion cell will typically have a cell voltage of 3.7V, compared to 1.2V for a typical Zinc-Carbon or Alkaline cell. This means fewer cells are required when using Li-ion technology. This makes Li-ion batteries ideal for portable power sources, mobile phones, laptop computers, and even electric cars.

Li-ion rechargeable batteries

FROM **$9.95**

NIPPLE CAP OR SOLDER TAB OPTION

A range of nipple cap and solder tab batteries in varying capacities.
SB2300-SB2319
Full range available in-store or online

LiFePO4 rechargeable batteries

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LONG LIFE CYCLE

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USB rechargeable Li-Po Battery

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USB

3.7V 1200mAh 18650 lithium polymer batteries with built-in USB charger. No cables, charger required! SB2309

Need a replacement battery? We stock a huge range of replacement batteries from tiny button cells to rechargeable batteries in all shapes and sizes.

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Drop in replacement for most lead acid batteries. More reliable with faster recharging and reduced number of charges.

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20A MPPT solar charge controller for lithium or SLA batteries

Uses Maximum Power Point Tracking (MPPT) for maximum efficiency and charge rate. Charge lead acid (sealed, gel or flooded) or lithium batteries. 3-stage intelligent charging. 12/24V operation. MP3741 **WAS $199**

SUPPLIED WITH 3 CHARGING CABLES

- **50A ANDERSON CONNECTORS**
- **LARGE BATTERY CLIPS**
- **EYE TERMINALS**

ONLY **$349**

Multi-stage charger for lithium and lead acid batteries

Charges 12V and 24V Lead Acid, AGM and Lithium (LiFePO4) batteries from 50Ah to 300Ah, with or without load. Automated 5-stage charging for Lead Acid and 2-stage charging for LiFePO4 batteries. 12V 30A or 24V 15A output. MB3621

Universal battery tester

Tests most types of small rechargeable batteries, including a huge range of Lithium-based (LiFePo4, Li-ion etc) batteries. Test voltage, capacity and internal resistance. QP2260 **WAS $34.95**

NOW **$29.95**

SAVE $5

Interlocking battery brackets - pair

Holds 18650 Lithium batteries together.
Dual PH9256 **$1.80**
Triple PH9258 **$1.95**

FROM **$1.80**

your destination for

power monitoring, saving & protection

240VAC

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AC power meter with LCD

Ideal for monitoring energy usage for large appliances such as a refrigerator, washing machine, air conditioner, etc. Display AC voltage, current, power and energy. Measure between 80 - 260VAC up to 20A. QP2325

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Take readings from hard to reach places where the powerpoint is not in clear view. Smart design with an LCD detached from the powerpoint. Displays watts, cost, volts, amps, and CO_2 emission. MS6108 WAS $29.95

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DC power meters 6.5-100V with built-in shunt

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Display power, voltage, energy and current. Exceptionally handy for keeping an eye on your solar installation, generator, battery banks, and more. Large blue backlit display.

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Single RCD* (safety switch) outlet

Portable unit designed to cut power in a fraction of a second in the event of a fault condition preventing electrocution. 10A 240V rated. MS4013

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SAVE $10

Power point and earth leakage tester

Assess the safety of installed main sockets and earth voltages and identify dangerous electrical installations. Multiple testing options. IP65 rated enclosure. QP2004 **WAS $34.95**

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Energy saving lighting

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ORRP $49.95 NOW $19.95 SAVE $30
LB120 Tuneable White YN8450
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LB130 Colour Change YN8448
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Electronic transformers for LED lights

Designed to be used with LED lighting products that take a 12V power source.
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Connect these Smart Bulbs to your home Wi-Fi network and control it directly from anywhere.

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  Track real-time energy used
- **SAVE ENERGY**
  Reduce energy use up to 80% without brightness or quality loss
- **MANAGE REMOTELY**
  Control your lights anytime, anywhere with your smartphone via free app
- **CIRCADIAN MODE**
  Automatically matches light appearance to time of day

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SAVE UP TO $40

LED replacement lamps: High brightness, uses less power and lasts much longer compare to traditional halogen lamps.

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SAVE $8

2D fluoro 900 lumens

Upgrade the old fluoro's in your caravan. Cool white.
• 12VDC 9W
ZD0670 **WAS $29.95**

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SAVE $5

G4 waterproof 100 lumens

Suitable for use in recreational vehicles. Waterproof.
• 12VAC/DC, 1.5W
Warm White ZD0564 **WAS $14.95**
Cool White ZD0566 **WAS $14.95**

NOW $9.95 ea

SAVE $4

G4 230 lumens

Great for benchtop lighting, reading lamps, etc.
• 12VAC/DC, 2.2W
Cool White ZD0655 **WAS $13.95**
Warm White ZD0657 **WAS $13.95**

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MR11 230 lumens

Commonly used for caravan lighting, marine interiors, etc.
• 12VAC/DC, 2.2W
Cool White ZD0650 **WAS $14.95**
Warm White ZD0652 **WAS $14.95**

PROJECT: DC power meter

Winter is the time of year when energy cost becomes expensive, so it's best to keep track of how much power you're using! This simple device will measure how much power any DC device is using, using Arduino®.

Note: This project is for measuring DC devices only, this will not work for your wall socket!

SKILL LEVEL: Beginner
TOOLS: Drill, hot glue gun

SEE STEP-BY-STEP INSTRUCTIONS AT:
www.jaycar.com.au/dc-power-meter

1 × Duinotech Nano Board	XC4414	**$29.95**
1 × Monochrome OLED Display Module	XC4384	**$29.95**
1 × 30A Current Sensor Module	XC4610	**$9.95**
1 × DC Voltage RegulatorModule	XC4514	**$7.95**
1 × Jumper Kit	WH3032	**$4.50**
1 × Jiffy Box - Clear - 83 x 54 x 31mm	HB6005	**$2.95**
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KIT VALUED AT $92.81

Note: Project has 4 binding terminals, only 2 are shown

LED displays

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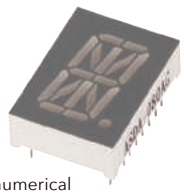
7 Segment
Numerical output display.
Red Common Cathode ZD1855 **$3.50**
Blue Common Cathode ZD1856 **$5.95**
Red Common Anode ZD1857 **$3.50**



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Alphabetical and numerical output display.
Green Common Cathode ZD1824
Green Common Anode ZD1826

half price!

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8 x 8 RGB LED matrix
192 LEDs in 64 pixels.
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Acrylic base for Uno and breadboard
- Self-adhesive rubber feet
- Measures 120 x 83mm

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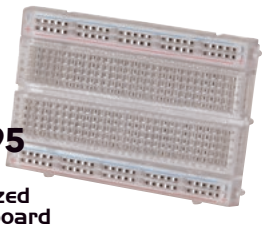

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Mid-sized breadboard
Prototyping breadboard with 400 tie points. PB8820

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ATTiny85 IC 8-pin DIP8
RISC-based microcontroller in an 8 pin DIP microcontroller. Operates between 2.7-5.5V. ZZ8721

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Breadboard power module
Adds a compact power supply to your breadboard. Power from a USB socket or DC. 3.3V or 5V switchable.
XC4606

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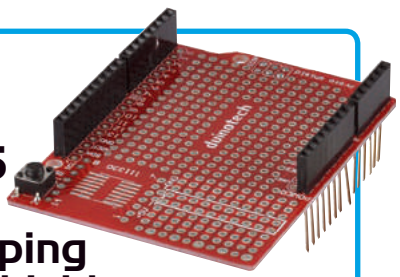

Prototyping board shield
Use a prototype shield instead of an LCD shield. This stackable shield makes semi-permanent prototyping simple. Includes reset button. SOIC-14 breakout, for surface mount ICs. XC4482

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ABS jiffy boxes
Sizes are compliant with industry standards externally and PCB fitting internally. Black/grey colour option.
HB6005-HB6025

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LED pack 100pcs
Contains 3mm and 5mm LEDs of mixed colours. Even includes 10 x 5mm mounting hardware FREE!
ZD1694 **WAS $29.95**
See website for full contents.

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SAVE $4

LED tester
Checks function, brightness, colour and polarity of light emitting diodes (LED).
- Test currents: 1mA, 2.5mA, 5mA, 10mA, 20mA,50mA

AA0274 **WAS $13.95**

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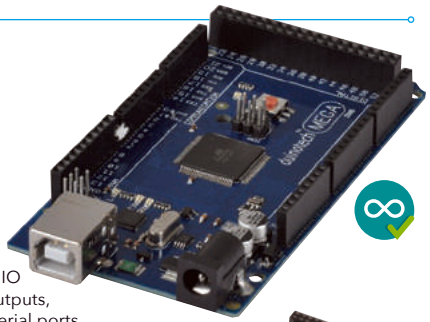

Our most powerful Arduino™ compatible board. Boasting more IO pins, more memory, more PWM outputs, more analogue inputs and more serial ports.
- 256kb program memory
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XC4420

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UNO with Wi-Fi board
An Arduino compatible UNO board with an integrated ESP8266 board to connect your projects to the cloud. No additional modules required. XC4411

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Mega with Wi-Fi board
An Arduino + Wi-Fi Dual board that includes a traditional Arduino chip + layout as well as an ESP8266 chip to connect your projects to the cloud. XC4421

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LED traffic light module
Set up a basic status display for your next project. 10mm red, yellow and green LEDs. XC3720

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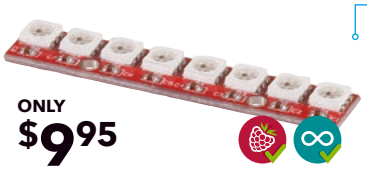
3W 200 lumen LED module
High brightness LED in an easy to use modular package. Includes a PWM input for brightness control. 5V. XC4468



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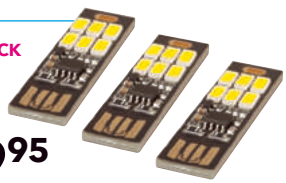
RGB LED strip module
Daisy chain up to 1000 LEDs run from one pin. 256 brightness levels. 5V. 54mm long. XC4380

3 PACK



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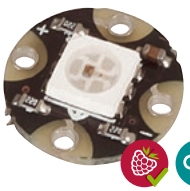
USB mini LED touch light
Touch control - ON/OFF (quick touch), Dimming (continuous). Double USB design. Compatible with all standard USB devices such as power banks, mobile chargers, etc. ZD1688



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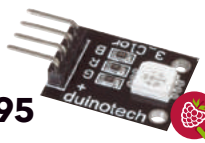
WS2812 RGB LED module
Provides full PWM control of the three LED channels in a single IC. ZD0272



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RGB LED module
4 pin header. Can be interfaced with a variety of microcontrollers. XC4428

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3D printer

Constructed from rigid all-metal frame design and body side panels made of high-strength ABS material. Stable print performance and durable. Features are assisted levelling, filament-run-out detection, file preview and more.
- 5" full colour touchscreen panel
- Wi-Fi, USB & Ethernet connect
- Resume printing from power failure
- Supports multiple mainstream filament types for diverse printing needs
- Prints up to 280(L) x 250(W) x 300(H)mm

TL4240 **WAS $2499**

See website for more details.
Note: As the item is huge, it is not available in all stores but we can easily get one for you. Please call your nearest store to check stock availability.

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DIY 3D printing book
This book will guide you to how to operate powerful, free software from Autodesk and bring your creations to life. Fun projects, easy-to-follow instructions, and clear screenshots.
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Ideal tape for coating 3D printer beds. 33m long.

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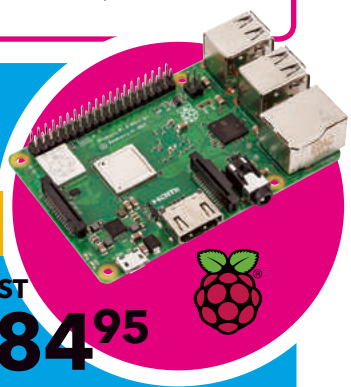

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Tiny credit card size computer.
- **1.4GHz 64-bit quad-core processor**
- **Dual Band 2.4GHz & 5GHz Wireless LAN**
- **Bluetooth® 4.2 technology with BLE**
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XC9001

16GB noobs SD card
Comes pre-loaded with NOOBS software for easy installation of Raspbian operating system. XC9030 $24.95

Power supply for Raspberry Pi
5.1V 2.5A. Provides all the power you need for even the most power-hungry. MP3536 $22.95

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NA2830, NA2832, NA2834
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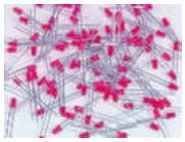
4.8V 3.4kg.cm. 6V 4.20kg.cm.
YM2760 **REG $19.95 CLUB $12.95**



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5-20mcd @ 20mA. Pk100. Red.
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RJ45 to RJ45. Blue.
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IP65 sealed ABS enclosure
171(W) x 121(D) x 55(H)mm.
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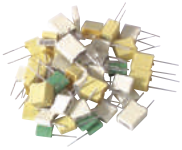

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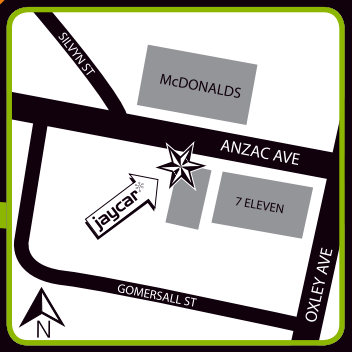

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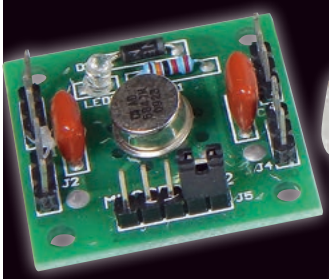
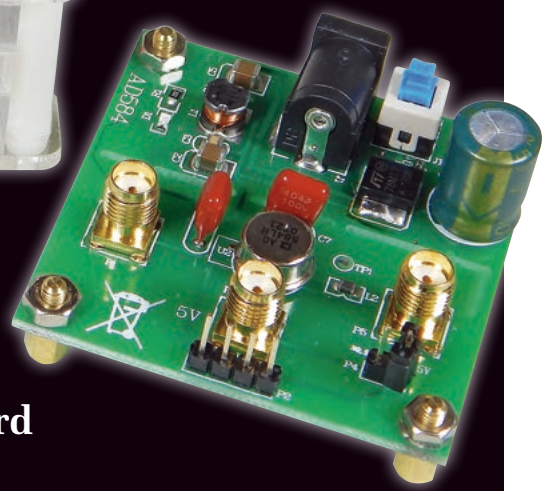
AD584 Precision Voltage References





These three low-cost precision voltage reference modules are based on the AD584 IC from Analog Devices, but each uses a different version of it and have unique designs. Two are 'naked' boards while the third comes in a transparent laser-cut acrylic case.

The ML005-V1.2 is the smallest module, with a PCB measuring 32 x 32mm. You can purchase it from AliExpress for around $3.25 (including delivery): www.aliexpress.com/item//32853943748.html

The slightly bigger module has no ID, but its PCB measures 50 x 50mm and it is available from Banggood for around $21 (including delivery): siliconchip.com.au/link/aaof

The largest module, from KKMOON, comes in an acrylic case, measuring 70 x 52 x 35mm overall. It is available from suppliers like Banggood and eBay for around $23 (including delivery): siliconchip.com.au/link/aaog

Each of the modules are based on different versions of the AD584 precision voltage reference device made by Analog Devices (the datasheet can be found at siliconchip.com.au/link/aaoh). Let's start by looking at how this chip works.

The AD584 device

Analog Devices describe the AD584 as a "Pin Programmable Precision Voltage Reference". It comes in a number of versions, all of which are available in an 8-lead hermetically sealed TO-99 metal package. The two lowest-precision versions are also available in an 8-lead plastic DIP. The metal package versions have an "H" suffix, while those in the plastic package carry the "NZ" suffix.

All versions are made using laser wafer trimming (LWT) to adjust the output voltages and also their temperature coefficients. Originally, five versions were available: the AD584J, AD584K and AD584L, all specified for operation from 0-70°C; and the AD584S and AD584T, which are specified for operation between -55°C and +125°C.

However, the AD584LH version was discontinued by Analog Devices in 2012, so presumably, those used in modules like the one described here are either 'new old stock' (NOS) or have been 'recycled' from used equipment.

The basic specifications of the AD584JH, AD584KH and AD584LH are summarised in Table 1; which can be found at the end of the article. The AD584JH version is the least accurate, while the AD584LH is the most accurate. But note that all three versions have identical specifications when it comes to noise output and long-term stability.

A simplified version of the AD584's internal block diagram is shown in

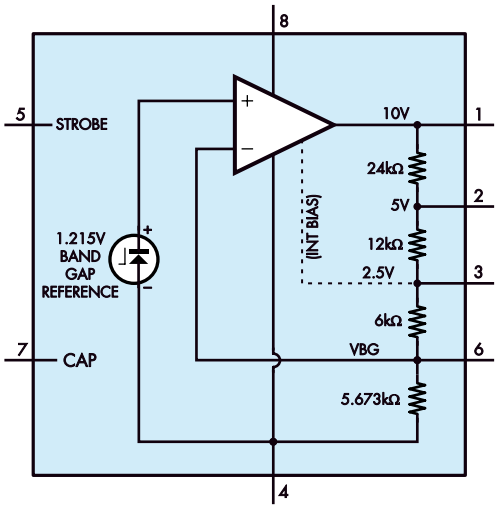
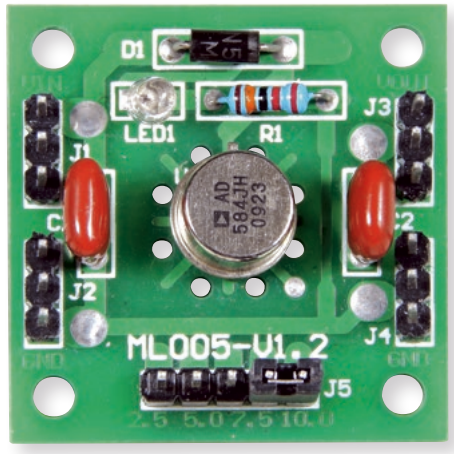


Fig.1 (left): the AD584 voltage reference IC used in all these modules contains a very accurate and stable 1.215V laser-trimmed bandgap reference, plus a precision op amp and resistors to amplify that reference to provide four possible output voltages (2.5V, 5V, 7.5V & 10V) depending on which combination of pins 1, 2 & 3 are tied together.

Right: the ML005-V1.2 module shown at nearly twice actual size. Note that searching for "ML005" online will not find this module, so you will need to search for AD584.



INSIDE THE AD584 CHIP

Fig.1. At the heart of the device is a high stability band-gap reference diode providing a 1.215V reference. This is followed by an op amp used as a buffer amplifier, with its voltage gain set by the string of divider resistors connected between its output (pin 1) and common (pin 4) terminals.

Internal feedback from the lowest tap of the divider string (pin 6, V_{BG}) ensures that the buffer amp maintains V_{BG} at very close to 1.215V, the band-gap voltage. So if a DC voltage between +12-15V is applied to the device between pins 8 and 4, and no external connections are made to pins 2, 3 or 6, it will provide a nominal output voltage of very close to 10V at pin 1.

But if pins 1 and 2 are joined externally, the voltage at pin 1 will drop to very close to 5V, and if pins 1 and 3 are joined, it will be very close to 2.5V. If pins 2 and 3 are joined, it will settle very close to 7.5V.

Notice also that pins 1, 2 and 3 can be used to source 10V, 5V or 2.5V independently, although pins 2 and 3 cannot provide significant current without affecting accuracy and so if used, the voltages should be fed through unity gain buffers. More on that later.

Note that you can't get a buffered 1.25V output from pin 1 by tying pins 1 & 6 together, turning the op amp into a unity gain buffer. This is because the 2.5V tap is used for internal biasing.

There are two pins we have not yet explained in Fig.1: pin 7 (CAP); and pin 5 (STROBE). Pin 7 is provided so you can connect a small capacitor (usually 10nF) between this pin and pin 6 (V_{BG}), to lower the bandwidth of the internal op amp and reduce the output noise level.

Pin 5 is provided to allow the AD584 to be switched on or off by a logic signal. If no current is drawn from pin 5, the device operates normally, but if the pin is pulled down to common/ground, it effectively switches off.

Now let's look at how it's used in the lowest cost module of our three.

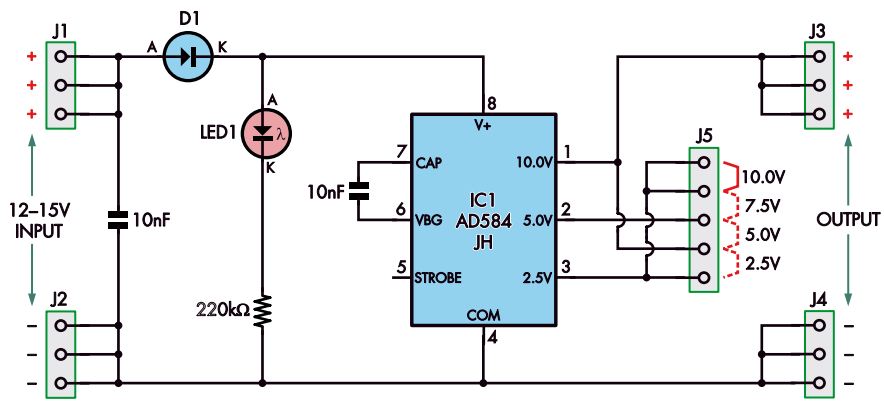
The ML005 module

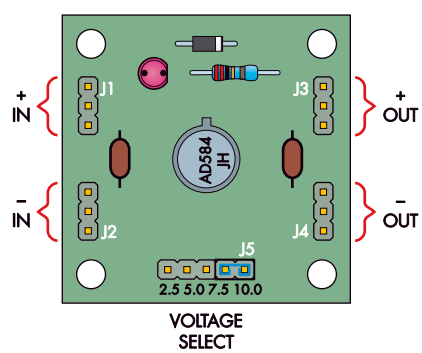
Fig.2 shows the full circuit of the ML005 module, plus the basic map of its PCB. As you can see, this module is essentially a 'bare minimum' design. It contains little more than the AD584 chip plus a few support components and some SIL headers used for input and output connectors, and for programming the desired output voltage.

It uses the "JH" version of the AD584 chip, so we shouldn't expect too much from it in terms of output precision or temperature stability.

Diode D1 is presumably to protect the AD584 from damage from reversed supply polarity, while LED1 and its rather high-value series resistor is to provide power-on indication.

The 10nF capacitor connected between pins 7 and 6 of the device reduces the output noise level, while





ML005 PRECISION VOLTAGE REFERENCE MODULE

Fig.2: the circuit and general layout of the basic ML005 reference board. It's a minimalist implementation of an AD584-based voltage reference, with pin header J5 provided to select the output voltage using a jumper shunt.

SIL header J5 allows setting the module's output voltage by fitting a jumper shunt to one of the four possible positions.

The current drain of the module when operating is less than 1mA, but this will rise if current is drawn from any of the outputs.

Before we move on to look at the next module, you might like to know how easy it is to give the ML005 module three fixed and buffered outputs of 10V, 5V and 2.5V.

Fig.3 shows all you need to do this: a low-cost dual op amp like the LM358 or the TL072, wired as shown to provide two unity gain buffers. One is for the 5V output of the module, and the other for the 2.5V output. The 10V output is already buffered by the op amp inside the AD584, so it doesn't need any further buffering.

Note though that this buffer op amp's "input offset voltage" error term will slightly reduce the accuracy of the output voltages, although typically this figure is no more than a few millivolts.

However, it can change with temperature and time. So if you need maximum accuracy, use a precision or chopper stabilised op amp, which will have offset voltages in the microvolt range.

So is it possible to trim the outputs of the ML005 module, to set the output voltages closer to nominal? Yes, it is, using the trimming circuit shown in Fig.4. As you can see it's fairly straightforward; just a 10kΩ multi-turn trimpot connected across the output from J3 (V_{OUT}) to J4 (0V), with a 10kΩ resistor in series and with its wiper connected to the 2.5V pin of J5 via a 3.3MΩ series resistor.

This allows the outputs to be adjusted over the range of about ±20mV; more than enough to achieve calibration.

The trimpot should be a 25-turn cermet unit, to allow fine adjustment and also provide a low temperature coefficient. The two fixed resistors should also be metal film types. The 3.3MΩ series resistor can be reduced in value for a wider adjustment range, but its value should not be lower than 300kΩ as this would adversely affect the module's stability.

The KKMOON module

Now we turn our attention to the module with all the 'bells and whistles'; the KKMOON (www.kkmoon.com/p-e0555.html). It comes housed in a laser-cut transparent acrylic case. The case can be easily disassembled for servicing, if needed.

The designers of this module seem to have gone out of their way to add every feature they could think of.

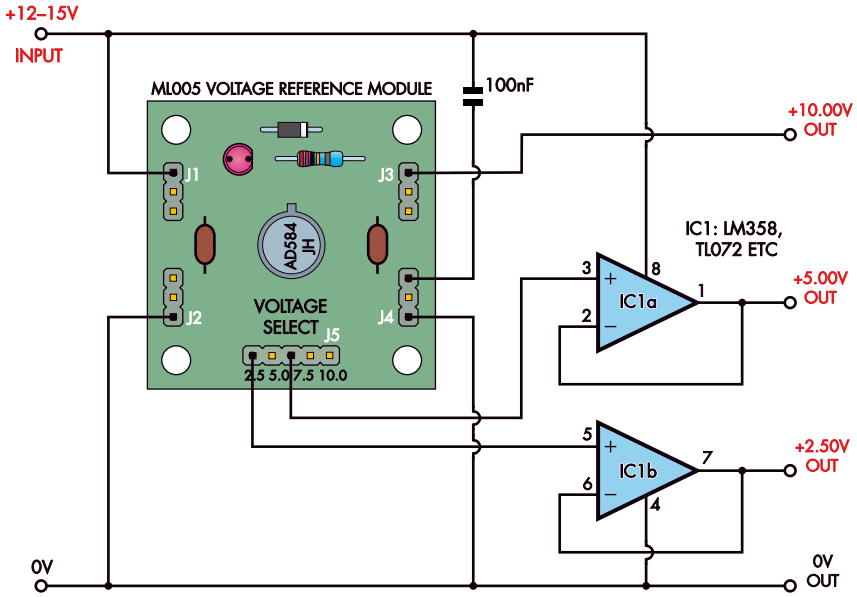
For a start, they've built in a 3.7V/500mAh lithium-polymer (LiPo) battery, so the unit can be used away from mains power.

Of course, the battery will need to be charged when you are back in your workshop, so they've built in a charger as well, with a 5V input (microUSB socket).

Since the battery only provides about 4.2V even when fully charged, they've also included a DC/DC boost converter to step up the battery voltage to around 13.5V for the AD584.

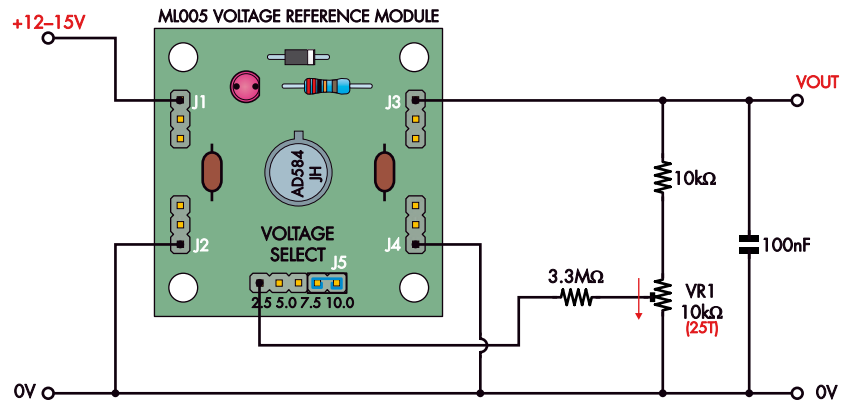
They've also added circuitry so that the various voltage ranges of the AD584 can be selected in sequence using a single pushbutton switch and LEDs to indicate which output voltage is currently selected.

The circuit (Fig.5) shows the parts they have added to provide all these



SC ©2019 GIVING THE ML005 MODULE THREE FIXED, BUFFERED OUTPUTS

Fig.3: this circuit shows how to get multiple different reference voltages from the ML005 module simultaneously. While you could use a low-cost dual op amp as suggested here, the voltages would be more accurate and stable if a precision or chopper-stabilised op amp was used.



SC ©2019 TRIMMING THE ML005 10V/7.5V/5V OUTPUT LEVELS

Fig.4: it's quite easy to connect a trimpot to the ML005 module, so that you can adjust its output voltages to be close to the nominal values. You need a very accurate voltmeter to do this. This will work with the output voltage set to one of the 10V, 7.5V or 5V options.

extra features. The heart of the unit is still the AD584 (IC1). The "KH" version of the AD584 is being used in this module – the one with performance specifications about twice as tight as those of the "JH" version.

All of the circuitry at the top and far left in Fig.5 is associated with the unit's battery power operation. The Li-ion cell is charged via IC2 at upper left, using power from a 5V USB source fed in via CON1. IC2 is a Linear Technology LTC4054 charge controller, with pin 3 connected to the positive pole of the cell.

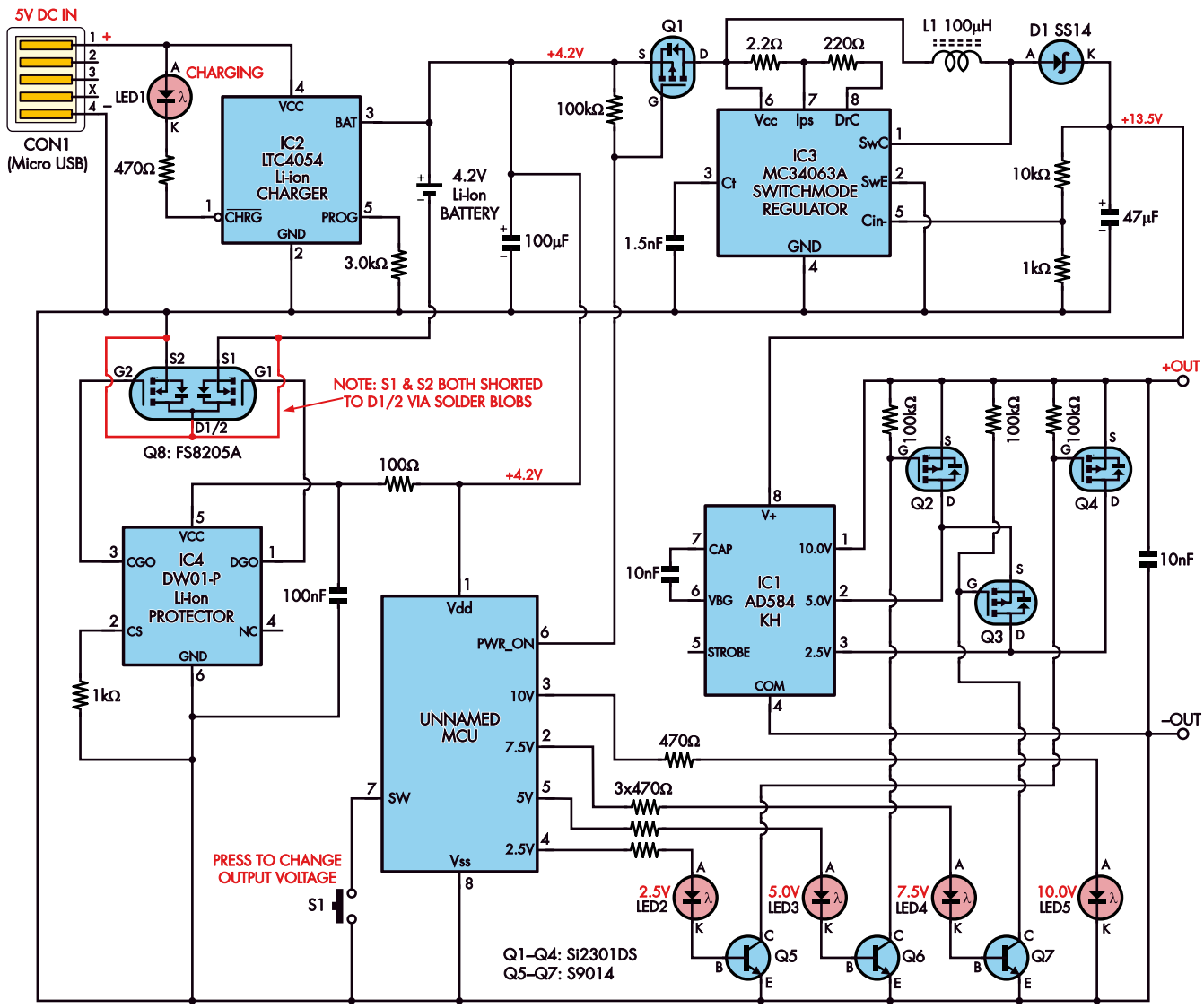
The resistor connected from pin 5 of IC2 (PROG) to ground sets the charging current level, while pin 1 of the device ($\overline{CHRG}$) goes low when charging is taking place. It's used to indicate when the battery is being charged, via LED1.

The circuitry at centre and lower left is intended to protect the Li-ion battery from damage from overcharging or over-discharge. IC4 is a DW01-P "Li-ion protector" chip which monitors the battery voltage via its V_{CC} pin (pin 5) and controls battery charging and discharging via pins 3 (CGO) and 1 (DGO), connected to the gates of Q8, an FS8205A dual N-channel power Mosfet.

However, oddly, in the modules we've seen, the sources and drains of Q8 are shorted together by solder blobs, disabling the protection circuitry by permanently connecting the negative side of the battery directly to ground. Perhaps this has been done because the LTC4054 has its own protection circuitry, which may well be sufficient for this application.

IC3 and its associated circuitry at upper right is the boost converter which steps up the Li-ion battery voltage to around 13.5V, to run IC1. It's a standard configuration using the MC34063A switchmode converter chip. Mosfet Q1 is used as an on/off switch for the boost converter, and hence for IC1 as well.

It's controlled in turn by IC5, shown at lower centre, which is an unmarked microcontroller unit (MCU) in an 8-pin SOIC package. The MCU is also used to perform the output voltage switching of IC1, as well as the indication



KKMOON AD584KH BASED PRECISION VOLTAGE REFERENCE

Fig.5: the circuit of the KKMOON voltage reference module is substantially more complicated, since it includes a DC/DC converter to boost the Li-ion battery voltage to a suitable level as well as battery protection, a battery charger and output voltage selection via pushbutton S1.

of the selected output voltage. This is all in response to presses of switch S1, connected between the "SW" pin of IC5 and ground.

Different outputs of IC5 are used to select the various output voltages available from IC1 by switching on one of the transistors Q5, Q6 or Q7, which then in turn switches on one of the P-channel Mosfets Q4, Q2 or Q3. These latter devices perform the same purpose as the jumper shunt links on the ML005 module (see Fig.2).

The LEDs indicating which voltage is selected are powered by the base drive currents for Q5, Q6 or Q7.

Because none of the links need to be fitted for IC1 to deliver its 10V output (ie, all those transistors are switched off in this case), the MCU simply activates LED5 via its "10V" output (pin 3) when that output voltage is selected.

So the KKMOON module is much more complex than the ML005 we looked at first, which probably explains why it costs about seven times as much. But it does offer a number of extra features, like portable operation and control using a single button. It also uses the superior AD584KH.

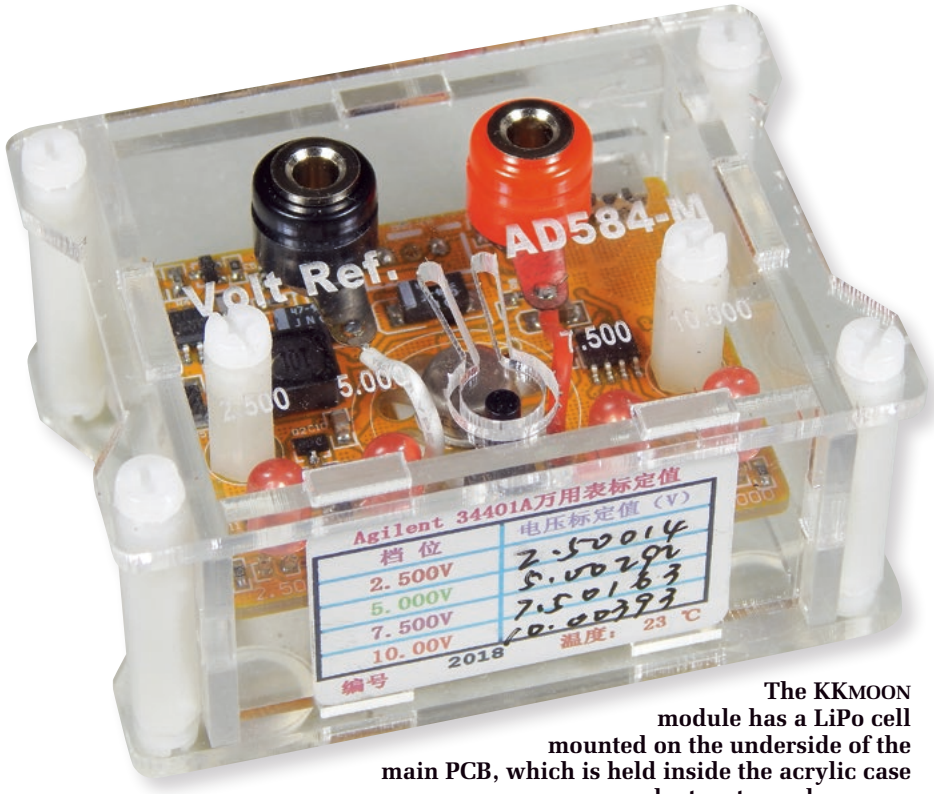
Mind you, using a high-frequency step-up converter to provide the 13.5V supply for IC1 might increase the noise level, while using Mosfets Q2-Q4 to select the lower output voltages might also turn out to have unexpected consequences. We'll look at these aspects a little later.

The unnamed module

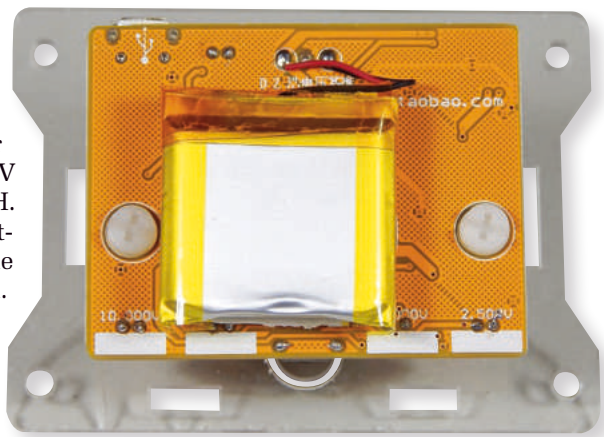
The third module is the one on a 50 x 50mm PCB, which carries no ID as such but is marketed as a 'high precision' module. This is perhaps because it features SMA coaxial connectors for the three main outputs, and is also claimed to use the AD584LH chip, which has the tightest specs of all versions.

The only aspect of the AD584LH which raises one's eyebrows is that, as mentioned earlier, it was discontinued by Analog Devices in 2012, suggesting that the makers of this module either bought a large quantity before then and are still using them up, or that they have salvaged some from used equipment. That's assuming they are genuine AD584LH devices, of course.

The circuit for this module is shown in Fig.6. It's much less complex than the KKMOON module, and only a little more complex than the ML005.



The KKMOON module has a LiPo cell mounted on the underside of the main PCB, which is held inside the acrylic case by two tapped spacers.



It's designed to run from 15-24V DC, fed in via J1, a standard concentric power jack. S1 is the on/off switch, while regulator REG1 derives a steady +12V to power IC1, the AD584LH. RF choke L1 and its associated capacitors ensure that the supply to IC1 is quite clean. LED1 provides a power-on indication.

Apart from the use of SMA sockets for the 10V, 5V and 2.5V outputs from IC1, the rest of the circuit is similar to that of the ML005 module.

However, there are two subtle differences, apart from the different AD584 version. One is that if you want a 7.5V output, this can be achieved by fitting a jumper shunt to SIL header P4. Then, SMA socket P1 delivers 7.5V rather than 10V.

The other difference is that the three main outputs of IC1 are also brought out to four-pin header P2, together with a ground connection. This may not seem significant, but it does make it easy to connect a voltage trim-

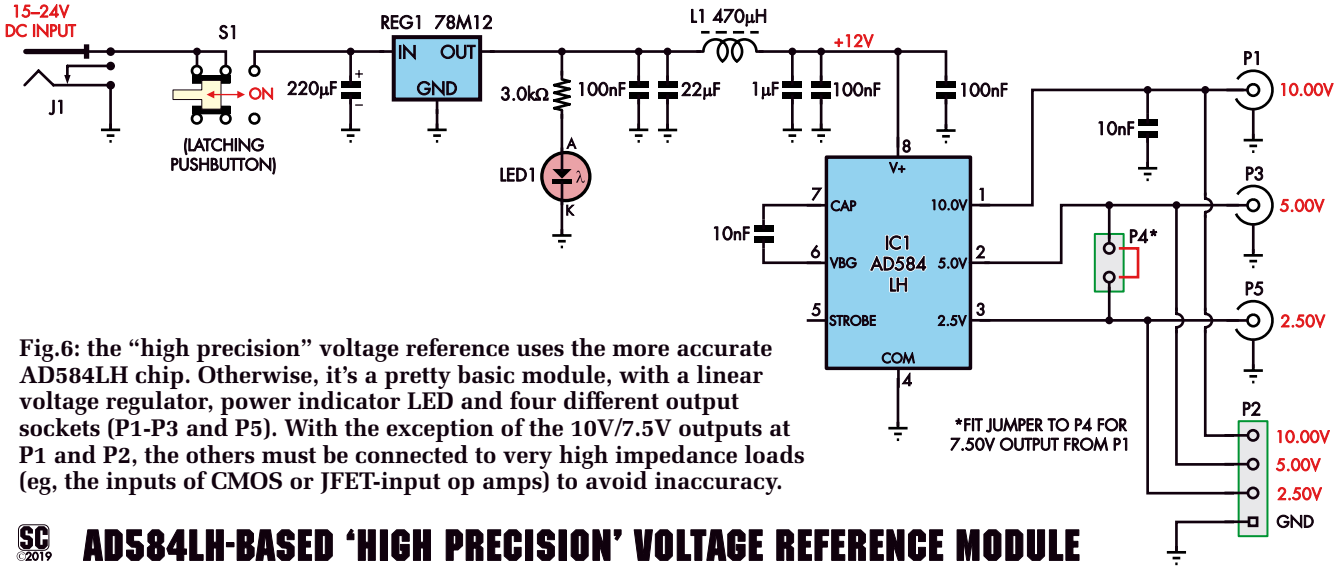


Fig.6: the "high precision" voltage reference uses the more accurate AD584LH chip. Otherwise, it's a pretty basic module, with a linear voltage regulator, power indicator LED and four different output sockets (P1-P3 and P5). With the exception of the 10V/7.5V outputs at P1 and P2, the others must be connected to very high impedance loads (eg, the inputs of CMOS or JFET-input op amps) to avoid inaccuracy.

AD584LH-BASED 'HIGH PRECISION' VOLTAGE REFERENCE MODULE

ming adaptor like that shown in Fig.4 to this module.

Trying them out

When we received the three modules, we put them through their paces. In each case, we applied power and allowed the module to warm up and stabilise for about one hour.

At the same time, we also switched on our very accurate Yokogawa 7562 6-1/2 digit DMM, and allowed it to stabilise as well. We then measured the four different DC voltage levels from each module, along with the noise levels, as shown in Table 2.

Overall, the output voltages from each module were within the specifications given by Analog Devices for the AD584 version used in that module.

In fact, the measured output voltages from all three modules were all within the specs given for the superior AD584LH device, with those for the ML005 and the KKMOON modules actually tighter/better than those for the module using the actual AD584LH. How surprising!

The box for the KKMOON module came with a stick-on label listing the actual output voltages for that module as measured at 23°C using an Agilent 34401A DMM. These were shown as 10.00393V, 7.50163V, 5.00292V and 2.50014V. Our measured figures were quite close to these, as you can see.

The ML005 module didn't come with any equivalent figures, but the module using the AD584LH device had a similar stick-on label on the sealed plastic bag it was packed in.

This "high-precision" module did not state the meter that had been used to make the measurements, but they were shown as 10.004V, 7.503V, 5.003V and 2.501V; again within the AD584LH specs and also quite close to the figures we measured.

Our measurements for the noise levels from each module are somewhat higher than the AD584 specs would lead you to expect, although they're still quite low.

This might be due to a shortcoming in the millivoltmeter used to make the measurements as its resolution below 1mV is rather poor.

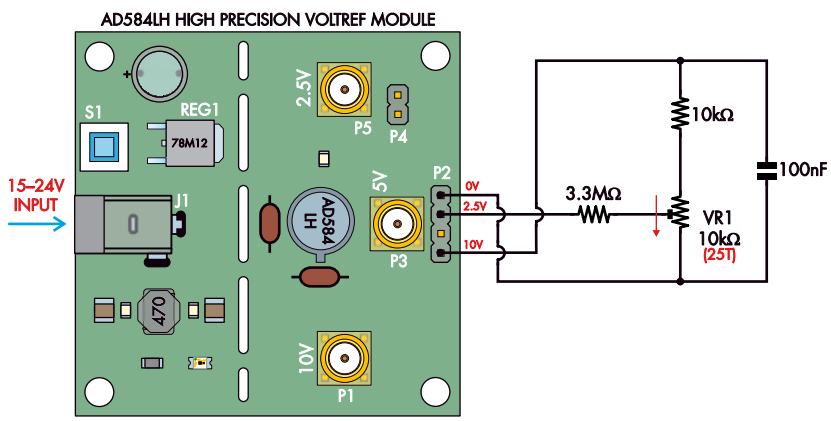
We were interested to see if there was any adverse effect on the output stability or noise levels of the KKMOON module outputs as a result of its use of Mosfets to control the output voltage and that high-frequency DC-DC boost converter, but we couldn't find any. The reference outputs of that module seemed to be just as stable and clean as those from the other two.

Trimming the AD584LH

The output measurements of the AD584LH-based module were a little disappointing, so we decided to try it out with a trimming adjustment adaptor. Fig.7 shows the adaptor circuit connected to the AD584LH module.

The components were fitted to a small piece of 'stripboard', with the 25-turn trimpot at one end and a 4-pin SIL socket at the other, to mate with pin header P2 on the module.

Using this simple adaptor we were able to adjust the 10.00497V output of the module down to 10.00003V at 26.4°C, with no increase in the apparent noise level.



TRIMMING THE AD584LH MODULE OUTPUTS

Fig.7: the voltage reference can also be trimmed with the addition of just four components. As this is the most stable of the references describe here, it would make sense to adjust it to be as close to the nominal voltages as possible. It should then remain accurate in the long term.

Table 1: basic specifications of the three main AD584 versions

PARAMETER	AD584JH	AD584KH	AD584LH*
Maximum Error for Nominal 10.000V Output	±30mV at 25°C	±10mV at 25°C	±5mV at 25°C
Maximum Error for Nominal 7.500V Output	±20mV at 25°C	±8mV at 25°C	±4mV at 25°C
Maximum Error for Nominal 5.000V Output	±15mV at 25°C	±6mV at 25°C	±3mV at 25°C
Maximum Error for Nominal 2.500V Output	±7.5mV at 25°C	±3.5mV at 25°C	±2.5mV at 25°C
Temperature Coefficient (10V, 7.5V, 5V outputs)	30ppm/°C (Ref 25°C)	15ppm/°C (Ref 25°C)	5ppm/°C (Ref 25°C)
Temperature Coefficient (2.5V output)	30ppm/°C (Ref 25°C)	15ppm/°C (Ref 25°C)	10ppm/°C (Ref 25°C)
Noise Output (0.1–10Hz)	50µV peak-to-peak		
Long-term Stability (drift)	25ppm/1000 hours		

* Note: this version was discontinued by Analog Devices in 2012. Modules with it may use recycled ('aged') devices.

Table 2: Measured performance of three AD584-based voltage reference modules

Module (AD584 version, supply)	Voltage Setting	Measured Output	Error	Meas. Noise Output
ML005 (AD584JH, 15V DC supply)	10.0V	10.00269V	+2.69mV = +0.027% or +269ppm	< 0.7mV RMS
	7.5V	7.49998V	–0.02mV = –0.00027% or –2.7ppm	< 0.5mV RMS
	5.0V	5.00185V	+1.85mV = +0.037% or +370ppm	< 0.3mV RMS
	2.5V	2.49876V	–1.24mV = –0.0496% or –496ppm	< 0.3mV RMS
KKMOON (AD584KH, 13.5V DC supply)	10.0V	10.00364V	+3.64mV = +0.0364% or +364ppm	< 0.3mV RMS
	7.5V	7.50143V	+1.43mV = +0.019% or +191ppm	< 0.3mV RMS
	5.0V	5.00280V	+2.80mV = +0.056% or +560ppm	< 0.3mV RMS
	2.5V	2.50011V	+0.11mV = +0.0044% or +44ppm	< 0.3mV RMS
'Hi Precision' (AD584LH, 15V DC supply)	10.0V	10.00497V	+4.97mV = +0.0497% or +497ppm	< 0.3mV RMS
	7.5V	7.50342V	+3.42mV = +0.0456% or +456ppm	< 0.3mV RMS
	5.0V	5.00300V	+3.00mV = +0.06% or +600ppm	< 0.3mV RMS
	2.5V	2.50129V	+1.29mV = –0.0516% or +516ppm	< 0.3mV RMS

DC voltage measurements taken with Yokogawa 7562 6-1/2 digit DMM (warmed up for one hour), at 25.8°C and 62% RH

It was then left operating undisturbed for four hours, during which the ambient temperature rose to 27°C and the measured output fell to 9.99997V – a drop of only 0.06mV or 60µV.

So our impression is that together with the trimming adaptor, the AD584LH module can be used to make a very stable and accurate voltage reference.

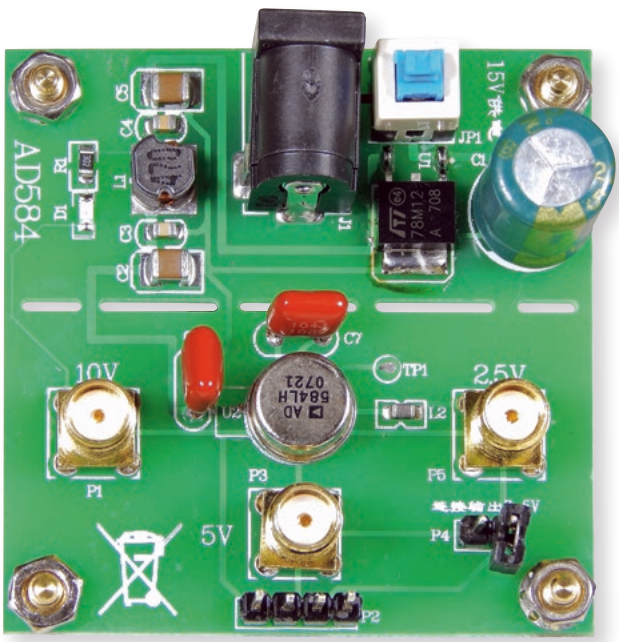
Which to choose?

If you just want a reference for checking 3-½ digit DMMs, analog meters and the like, the ML005 module would be ideal and has the price advantage over the other two modules.

But if you want a portable reference for checking instruments 'in the field', the KKMOON module would be the one to go for.

If you want the highest accuracy and stability, we'd suggest you choose the module based on the AD584LH device, together with the trimming adaptor circuit shown in Fig.7. This gives you a voltage reference comparable to commercial units costing over 10 times its modest cost of $23.

You can find a quick gestalt on the same three modules at siliconchip.com.au/link/aaoi SC



The alternative "high-precision" AD584-based module. It uses an AD584LH as opposed to the AD584JH used in the ML005 module. However, when measured, this module displayed worse accuracy than the other two.

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SERVICEMAN'S LOG

Repairs for a 'key' client

Dave Thompson

I'm getting a wider variety of items into the workshop for repair these days, and I've noticed that almost all are high-quality electronic devices which were generally manufactured before the 1990s.

It could just be that this is the age where equipment tends to fail, or folks who own appliances of that vintage are of a generation that typically loathes to bin their hard-earned possessions at the drop of a hat. But it's a sad fact that so much hardware these days is not built to the same quality as it once was.

Finding a replacement appliance made to the same standard as your old one can be frustrating (if not impossible), which is why many try to extend the useful life of existing devices by refurbishing or repairing them.

We also live in an economic climate where vendors and retailers aim for the lowest common denominator buyers, which usually means keeping the price low rather than keeping the quality high. So most modern appliances are built 'down' to a price.

Nevertheless, many appreciate quality and are prepared to spend more (sometimes, a lot more) on something well-built and made to last. Unfortunately, choices for those people are becoming more limited.

For example, I can go to the nearest 'big box' store and buy a ridiculously-oversized stereo/radio/DVD-player combo, with a blow-moulded plastic case, too-many gaudy flashing LEDs and an offensive amount of bass boost for a mere couple of hundred dollars.

But if I want anything decent, there's almost nothing between it and a very expensive, name-brand 100W/channel Class-AB reference amplifier, with rubber mountings, oxygen-free-copper transformers, hand-wired circuit boards and heavy-gauge matte-black steel case.

I'd much prefer this high-end amplifier, but would be soon destitute after purchasing the matching speakers, solid gold cables, Oracle turntable and Accuphase tuner to go with it. While the big-shed special will likely blow itself to bits after a few too many rowdy all-nighters, the high-end amp and components would easily see me out (and quite possibly whoever inherits it once I'm gone!)

Don't get me wrong, I'm a 'gearhead' at heart and am always looking for an excuse to buy a better mobile phone or upgrade my computer with the latest goodies; the difference is that I know these devices have a finite lifespan.

Given time though, even a $6000 amplifier can fail. Whether it's a scratchy potentiometer, a blown output transistor or a dried-out capacitor, these 'wear and tear' issues can usually be resolved quite easily, mainly because quality devices are designed to be disassembled and repaired in the first place.

A job arrives through the grapevine

Which brings me to my current challenge. A while ago, I repaired a Yamaha electric piano for a neighbour. To be honest, it wasn't a particularly taxing job, but it was laborious.

The sheer size of the thing and the number of fasteners, clips and plugs to undo makes working on large instruments a pain, especially with the limited bench-space in my small shop.

Another neighbour heard about that Yamaha repair and called me with her own tale of woe. She'd purchased a then top-of-the-line Roland KR-500 keyboard back in the 1980s. She didn't say what she'd paid for it, but it was likely a small fortune.

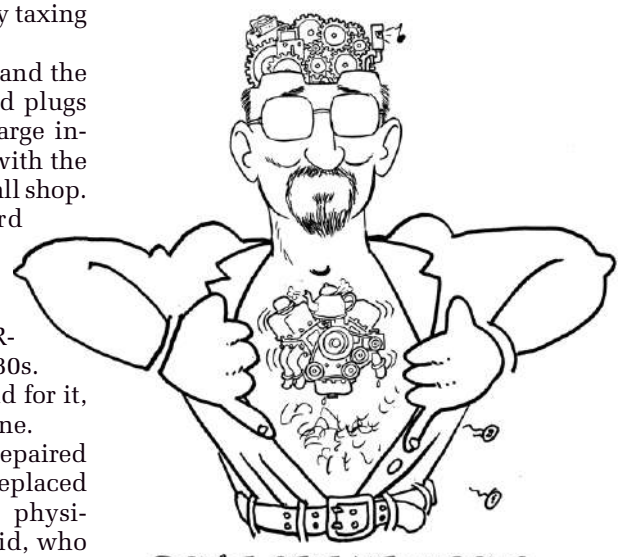
About ten years ago, it was repaired by a local music store; they'd replaced half-a-dozen keys that were physically damaged by a friend's kid, who thought playing it involved smashing the keys repeatedly with a timber block. Since then, it has been covered when not being played.

Recently, the owner noticed that one or two keys would intermittently not sound, and when a couple more started playing up, she sought out the same repair shop. Unfortunately, this business had closed after the quakes and had never re-opened.

The owner called around a few other music stores and was told the instrument was "too old" to repair. They all kindly offered to sell her the latest model, though!

Out of desperation, she'd shipped the thing up to the main Roland distributor in Auckland, who sent it straight back, stating that it was non-repairable. Given the size and weight of the keyboard, even without the solid-wood pedestal it is usually mounted on, transporting it to them and back would not have been cheap.

When she heard via the bush telegraph of a local who could fix keyboards (ie, me), she couldn't get on the

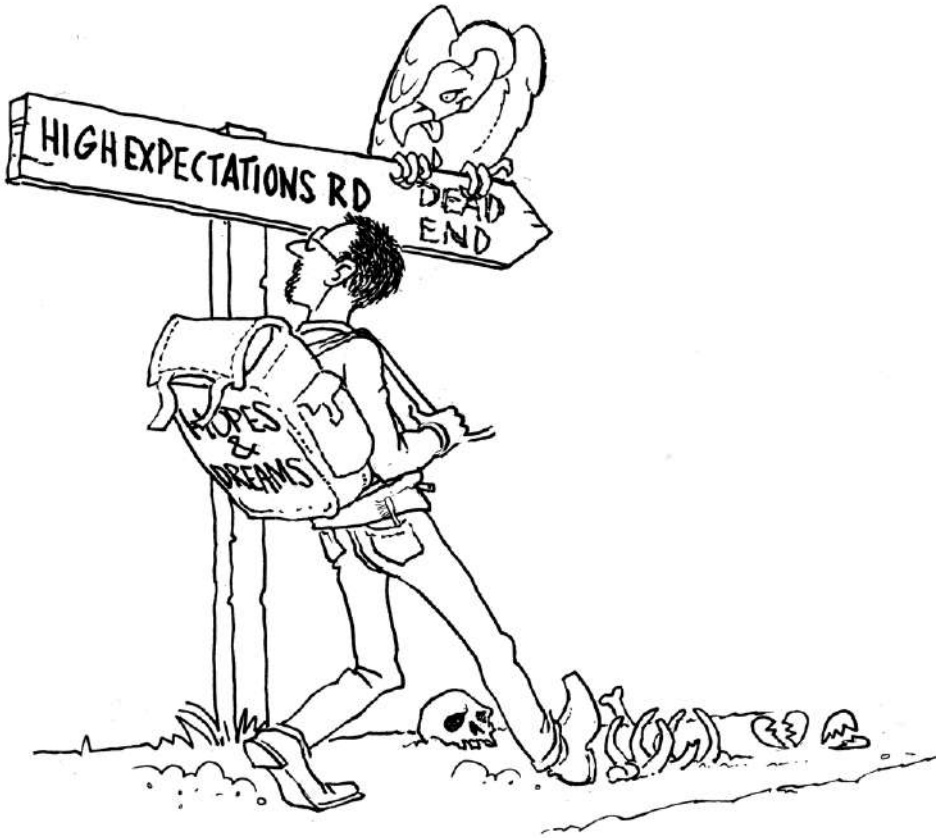


Items Covered This Month

- A keyboard without conductor
- 50W CO_2 laser tube replacement

**Dave Thompson runs PC Anytime in Christchurch, NZ.*

Website: www.pcanytime.co.nz
Email: dave@pcanytime.co.nz



I'VE BEEN DOWN THAT ROAD BEFORE

phone fast enough, asking if I'd take a look at this one.

I've been down High Expectations Road before, so I told her all I could do was open it up and see what was going on. After that, we'd know the way forward – if any. She was OK with this and happy to pay for my time. I also suggested that I come and look at it first; if it was going to be an obvious non-starter, this would save some effort.

It turned out that she lived literally around the corner. This KR-500 is pristine, a vision in vintage dark-brown, looking for all intents and purposes as if she'd just had it delivered from the shop. It didn't have a mark on it, and even though it had been well-played, it showed none of the usual wear-and-tear I usually see on older instruments.

I powered it up, and doing my best Rachmaninov impression, tested all 88 keys one by one; I found at least a dozen not working at all and as many intermittent.

The period-fashionable linear pots, LCD screen and all of the dozens of micro-switches and tiny red LEDs on the control panel appeared to toggle and work properly. So did the retro, analog (but still cool-sounding) 'rhythm' section. So the fault lay only with the keys.

I told her it was likely the keyboard contacts were causing problems and that a good internal clean might fix things. But if that didn't work, we'd have limited options.

She was happy for me to assess it further, so I arranged for her and her husband to remove it from the stand and bring it to my workshop in her van; my MG isn't the best vehicle for transporting full-sized piano keyboards!

Prepping the beast for surgery

In my small workshop, the keyboard looked even bigger. Like the majority of Japanese-made instruments of the era, it is incredibly well-built using long-lasting, high-quality materials.

Splitting the case was easy; just a matter of removing the dozen or so standard screws holding it all together. It was obviously made to be serviced, with the top section hinged at the rear corners to the internal metal chassis at the bottom. So after releasing the various power and ribbon cables linking the two halves, it simply opened up like a sandwich press.

The inside was as clean as the outside. These older keyboards have a lot of PCBs stacked with rows of large, VLSI integrated circuits. There are a ton of components compared to modern instruments, where one or two (likely proprietary) ICs would do the same job.

Here, all the parts were clearly marked and the circuit boards had screen-printed values and part numbers, so if I later found that I needed a circuit diagram, I would have no trouble figuring out how it corresponded with the actual hardware.

I made an educated guess that since most of the keys worked, the electronics were probably OK and the fault lay with the keyboard itself. After all, it's the component that's given the hardest time by the user.

Even though the rest of the keyboard may be pristine, over time all manner of rubbish, sweat and other unmentionables migrate down through the gaps between the keys to foul things up.

Most keyboards have this problem and there isn't a lot that can be done about it, other than avoiding smoking, drinking and perspiring while playing. Giving the keys a good wipe-down and a thorough hoover now and then helps too.

This keyboard assembly was a solid piece of kit. Built like the proverbial masonry ablutions domicile, the backbone frame is a z-shaped piece of folded, heavy-gauge steel securely bolted to the substantial timber bottom of the case.

Sections stamped out of the frame accommodate and hold the spring-steel key springs and other peripherals while a couple of 90cm-long flexible connectors span the length of the keyboard at the bottom, folding and splitting off at right-angles at the mid-point to connect to the main PCB.

After removing the whole assembly from the base and flipping it over, I could see a green, 'thin-film' circuit board peeking out from under the keys. The problems likely lay somewhere

within. I couldn't get any access at all to the circuit board or the contacts under the keys, so the only option was to remove everything from the frame.

This was a mission in itself. Along the top of the keyboard, flush with the 'heads' of the keys, were a series of plastic locking strips. These had been attached to the frame with very strong double-sided tape, and I had to carefully pry them off one by one.

Once off, each key could be pushed slightly forward to release the back 'hinge' and then maneuvered out of the frame. With the first key, the steel spring pinged off into the distance; fortunately, I found it after much foraging under the bench. I daren't lose any because re-creating them would be extremely difficult.

Getting to the heart of the matter

The PCB was dusty underneath, so my hopes rose that a good clean would sort it out. I could also now see the strips of grey rubber contact pads that make up the top half of the keyboard switches.

These were still looking very good and felt nice and supple; hopefully, the carbon-composite contacts moulded into the strips and their corresponding printed contacts on the circuit board below would be in a similar condition.

By now I could see the whole PCB, or at least most of it, given that some of it was still obscured by the rubber key switches.

The circuit board was in two halves; one for the lower four octaves and one for the upper four. These are stuck (probably with similar 'gorilla' tape) to the metal frame, and I really didn't want to have to remove them.

The fact that multiple keys up and down the keyboard were failing meant that the problem wasn't localised to one or the other circuit board, so it must be something in common with both causing these problems.

It didn't take long to find a potential smoking gun. At the end of each PCB is a multi-pin, thin-film joiner that curls under the frame to link up to the long flexible main-board connector strips beneath.

While there is a socket mounted on a bracket for the joiner's silver-coated contacts to push into, on the top the graphite or carbon pads are just pressed onto and stuck to the corresponding thin-film key PCB connections with conductive tape. This is all held down by a clear-plastic link pinned to the metal frame at each end with plastic push clips.

On closer inspection, I could see that the conductive tape had let go in places, making contact sporadic at best. I carefully plugged the piano in and positioned everything while the case was open so I could power it up.

With it switched on, I could press the rubber key contacts directly and with the right pressure on the flexible joiner connections at each end, could get the previously non-working keys to sound. I then used a couple of small-but-strong spring-clamps (like clothes pegs on steroids) to firmly hold these contacts in place while trying every key.

While they all worked, just tapping on the clamps resulted in dead keys again, so merely clamping something stronger than the existing plastic bar onto the connections wasn't going to work.

Figuring out how to make a lasting repair

There are 16 contacts each less than 1mm wide, separated by a similar-sized gap, on each joiner piece. I could see most of the original contact material had been stripped away by the lifting tape. I'd need to rebuild these contacts, and that could be a challenge.

I had to take a break and ponder the problem. My initial thought was to replace the strap with a computer IDE ribbon cable or similar; I could solder one end of it directly to the socket's PCB pads underneath, but I'd have to work out a way to connect the other end to the missing contacts at the thin-film PCB end.

Then I remembered conductive paint; I'd used this a long while ago to good effect. Perhaps it would work here. Maybe I could simply paint in the missing contacts and voila!

Feeling hopeful, I ordered some from an auction site, mainly because it was considerably cheaper than the paints listed on local electronics suppliers' sites.

However, when it arrived, I discovered it had gone off and was useless. While I arranged for a refund, I bit the bullet and shelled out $60 for a pen-style applicator with conductive silver paint from a more reputable source.

Annoyingly, this wouldn't work properly either; the contents had partially hardened. I'm still waiting to hear back from them, but in the meantime, I scooped a bit of the material from inside the pen and mixed it manually.

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It looked OK, so I painted it onto two of the contacts on the joiner. It looked the business, and after letting it dry overnight, I tried some continuity tests. It didn't conduct at all, and when I tried to remove it, I only succeeded in stripping more of the meagre amount of contact material remaining on the joiner! This effectively ruined it and ruled out using that option again. What to do now?

I went back to my ribbon cable idea and found an old floppy-disk cable. The wire spacing was identical to that on the socket PCB, so I peeled off 16 strands, cutting off about twice the length I'd need. I stripped 3mm of insulation and carefully twisted and tinned each wire. I then soldered the wires to the socket's PCB pads. This was the easy part; it was the other that caused me difficulty.

While long-time servicemen out there are probably eye-rolling and shouting into their magazines that I could have used product X or Y, I settled on using self-adhesive conductive copper tape to replace the half-missing contacts on the end of the thin-film PCB.

I cut the tape to precisely the right size, then stuck it down with enough left over to solder (quickly!) to the stripped and tinned ends of the ribbon cable. I then clamped the plastic link back with screws instead of pins and tested the keyboard.

This part of the keyboard now worked a treat, so after wrapping the joins carefully in polymer tape, I repeated the process on the other side. I cleaned everything, painstakingly reassembled the keyboard and got the owner over to test it out properly. The result was music to both of our ears!

50W laser tube replacement

This time, we had the opportunity to be our own serviceman. The laser tube in our laser cutter stopped lasing (it had one job!). This is how we got it going again...

We use our laser cutter to make custom case parts out of acrylic sheets for some of our projects. It is one of the "K40" types that can be purchased from any number of online stores.

It's a CNC machine; stepper motors move the head over the top of the workpiece. A 50W CO_2 laser provides the ability to cut and etch (by running the laser at reduced power) as the head moves around.

The cutter has a water cooling circuit to keep the laser cool, as well as a ventilation fan to remove the plastic vapours that are generated. There is also an "air assist" system which pushes fresh air past the lens, to keep it from being contaminated by dust and fumes, and to help burn away the plastic.

The laser cutter (laser and XY table mechanism) works quite well, although we did initially have some trouble with the ventilation and cooling components.

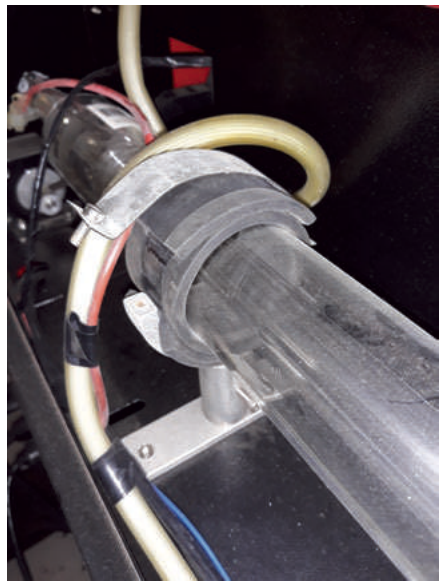
We documented our fix for these in an article in the June 2016 issue (siliconchip.com.au/Article/9960).

Since then, the laser cutter has performed well, until one day we went to check on the progress of a cutting job, and found that it had not only stopped cutting, but was emitting a high-pitched whine.

The laser is a fixed glass tube around a metre long which is fed from a high voltage supply; it's kind of like a neon tube on steroids.

The beam is reflected by three mirrors and focused by a lens onto a point directly below the moving head. The laser tubes do not have a long life span, and the four years that this one had been working appears to be par for the course.

When it was powered up, there was a corona discharge visible near the anode, but not the usual, healthy glow along the full length of the tube.



Left: the old laser tube with the water cooling tubes and supply wires detached.
Middle: the glass tube is mounted in a saddle lined with rubber pads, which had to be carefully removed.
Right: the anode wire join for the new laser tube.

We suspected breakdown of the high voltage insulation around the anode connection, and attempted repair by adding some silicone sealant.

Unfortunately, while that stopped the discharge, the laser still wasn't working, so we suspect that the critical CO_2 gas may have escaped through a small hole. Since the tube is blown glass, it's almost impossible to service. So we bit the bullet and ordered another tube.

After a few anxious weeks, the new tube arrived in one piece. This one was slightly different to that originally fitted to the K40.

For example, it has a slightly smaller diameter and is also a bit shorter. It generally looks a bit better made, and the high voltage anode lead features a locking insulating sleeve that protects and insulates the wire join we would have to make.

Thus began the delicate process of removing the old tube and replacing it with the new tube. We started by draining the cooling water circuit, using the cooling pump to empty it into a bucket. We then opened up the hoses near the laser tube and forced air in, to get the rest of the water out.

The tube is held in place by clamps at either end, with the glass tube protected by rubber pads which fully encircle it.

We cut the two supply wires (a red anode wire and a black cathode wire) near where they are terminated to the old tube, giving some extra length for connecting to the new tube. The new tube already had wires fitted and insulated to the anode and cathode, much more nicely than the old tube, so we wanted to keep as much of the wiring as possible.

After this, having already detached the cooling water tubes, we carefully removed the tube by lifting it out.

The new tube has a warning to refer to the user manual, but there was no manual included. So we were going to have to figure out the installation process by ourselves.

We fixed the new tube using the existing clamps. Its slightly smaller diameter meant that the hex machine screws had to be screwed in further than previously, but we were able to clamp it securely.

We then attached the water pipes. These merely push onto the barbs on the tube. All seemed in order, so we turned on the pump and refilled the small outflow tank with fresh water.

The cooling circuit quickly filled, and the bubbles made their way to the outflow pipe. It's important to get rid of air bubbles so that there aren't any hot spots inside the laser tube. Our cooling system monitor reported no faults, so the flow appeared to be adequate.

We then soldered the two new wires to the existing power supply connections, added heatshrink tubing and fitting the protective anode wire housing over the join.

These wires are very fine, but have very thick insulation due to the high voltage (tens of kilovolts!).

To avoid strain on the new splices, we taped the wires to the outside of the tube (as the original wires had been). This completed the installation, but we still needed to check the alignment of the laser with respect to the mirrors and other optics.

Calibration

Since the new tube has a smaller diameter than the old one, we expected that the line of the laser beam would be shifted somewhat. Removing and re-fitting the rubber pads may have also caused some variation. So we took no chances and checked the entire beam path.

This is done by placing a piece of paper (such as a self-adhesive label) over the mirror in the optical path, briefly firing the laser using the PULSE button, then checking that the laser strikes near the centre of each mirror along the way.

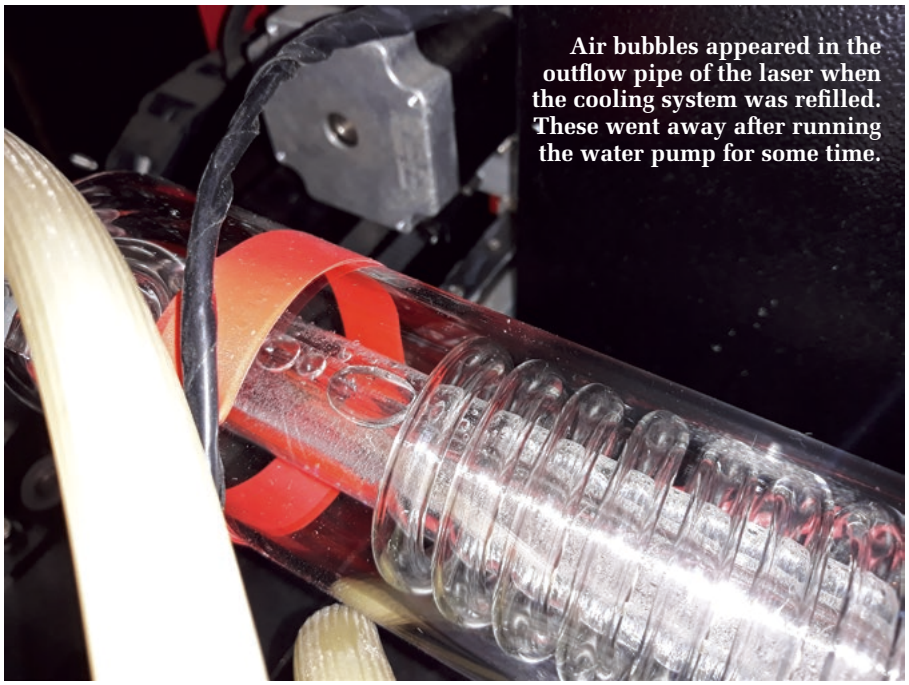
The first mirror is accessible from the rear of the machine, the second through a panel on its left side, and the third is on the moving carriage, directly above the lens which focuses the beam onto the workpiece.

We found a good guide at **siliconchip.com.au/link/aao9** The button press triggering the laser burst needs to be very brief, or the sticky label may smoulder or catch fire. After trying with a second sticky note, we found that the laser was aimed close to the

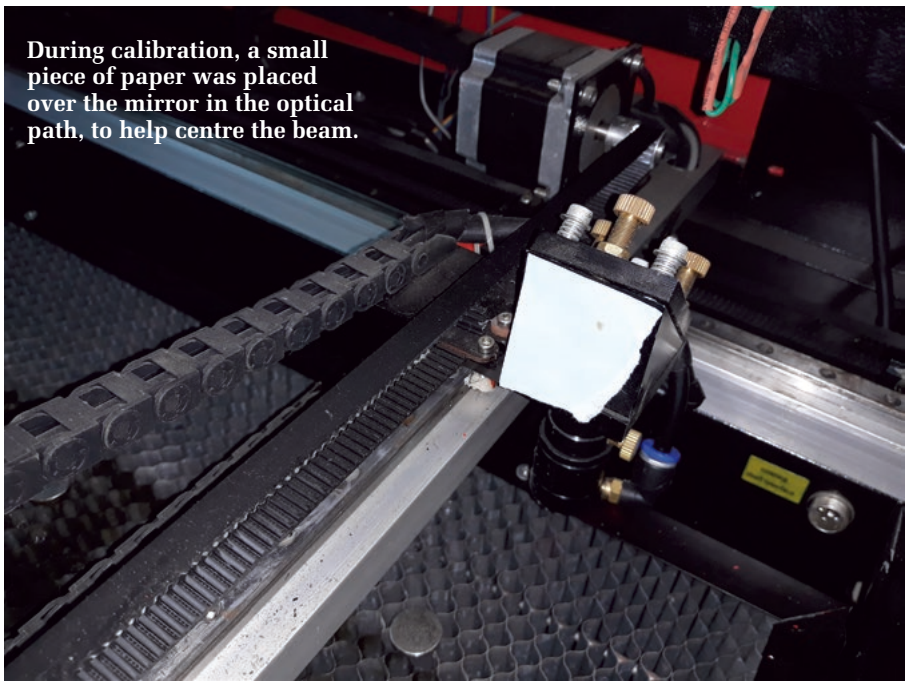
centre of the first mirror, which was no surprise, since it is close to the end of the laser tube.

Proceeding to the second mirror, we found that the beam was striking a little low. We adjusted this by turning fine-pitched screws on the back of the first mirror, changing its angle to aim it towards the centre of the second mirror. A fraction of a turn was all that was needed to correct the aim.

Repeating with the paper on the third mirror, we found that this was a little low too, so a similar adjustment was performed on the second mirror. The alignment test is repeated with the carriage in all four corners of the laser cutter bed, to ensure that the results are uniform. We found only a tiny amount of variation, so the beam alignment was complete.



Air bubbles appeared in the outflow pipe of the laser when the cooling system was refilled. These went away after running the water pump for some time.



During calibration, a small piece of paper was placed over the mirror in the optical path, to help centre the beam.

Testing

While checking the mirrors, we took the opportunity to clean them using acetone and a lint-free cloth. The cloth was dirty afterwards, so a clean was undoubtedly due.

The laser beam focusing is dictated by the distance between the beam and the bed; it should not have changed, but we decided to check it anyway.

We performed a 'ramp test' by placing a piece of acrylic on the bed, propped up at one end so that the cutting depth changes along the piece. We ran a cut, and the results showed that the focus was fine, as the cut was cleanest close to the bed.

We followed by running a job, and all seemed to be in order. By this time, we had quite a backlog of orders for case pieces, so we had to run the laser cutter continuously for several hours.

Disaster strikes

While setting up for one of these jobs, one of the hinges that holds the lid on snapped, leaving the lid hanging by the remaining hinge and the gas struts.

The lid had been getting quite hard to close, and appeared to have shifted, but now it was impossible to close as the gas struts were pushing the lid against the remaining hinge, threatening to break it too.

Due to the safety interlock, the laser will not operate unless the lid is closed, so this had to be fixed before we could continue.

Fortunately, Bunnings has an extensive range of hinges. Thus we did not have to wait weeks to get the laser cutter going again.

We took the broken hinge to the closest store and compared it to the hinges there, and found one that was a similar size and had a similar hole spacing at one end.

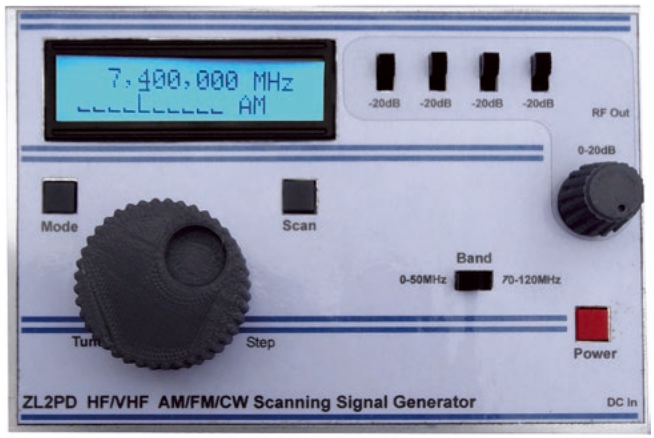
We removed the gas struts, as they pushed the lid around awkwardly, and in any case, it made it easier to work on the lid by detaching it entirely from the laser cutter.

Although the holes on the new hinges were in slightly different locations, by enlarging two holes on each and drilling six new holes in the lid, we got them to fit.

These hinges are a different style than the old ones and don't sit flush when fully open. So we inserted some spacers under them, to ensure that the laser protection switch would engage with the lid closed (the laser is disabled when you open the lid).

The new hinges work even better than the old hinges, with the lid not jamming so much and we were back up and running again less than a day later. SC

An AM/FM/CW Scanning HF/VHF RF Signal Generator



Part 2

by Andrew Woodfield, ZL2PD

We introduced this RF signal generator last month. It is an ideal entry-level test instrument for anyone into radio: capable, yet low in cost and quite easy to build. None of the parts are too hard to come by, either. . . Now let's get into building it – and getting it up and running. We also have some performance plots and instructions on how to use it.

The signal generator is built on one double-sided PCB coded 04106191, measuring 152.5 x 102mm. Refer to the PCB overlay diagram, Fig.5.

Most of the top (component-side) surface has been retained as a ground plane for added shielding. No SMD parts are used in the construction of the signal generator, making it relatively easy to build.

Start by fitting all the resistors where shown. It's best to check each part with a DMM set to measure ohms before fitting them, as the colour bands can be hard to distinguish (eg, brown can look like red, as can orange). Don't forget the 47Ω resistor hiding under S4!

Then mount diodes D1 and D2, ensuring they are orientated as shown. Next, mount the socket for IC1, with its notched end facing the top of the board.

Now fit the ceramic and MKT capacitors, which are not polarised. Don't get the different values mixed up though. There's also one of these under S4. Follow with trimpot VR1 and plastic package transistors Q1, Q2, Q4 & Q5. Q4 is a different type than the other three.

Next, solder 6-pin header CON3 and two-way headers CON4 and JP1 to the board, followed by the power socket (CON1) and then the electrolytic capacitors. These are polarised; in each case, the longer lead must go to the pad marked with a "+" on the PCB. The stripe on the can indicates the negative side.

Fit the three pushbutton switches, with the flat side orientated as shown in Fig.5, ensuring they are pushed down fully onto the board before soldering their pins. S3 is red while S1 and S2 are black. You now have almost enough components mounted to test the power supply.

It is recommended that you attach REG1 to the case for heatsinking, but we haven't built the case yet. Anyway, the easiest way to do this is to cut the three regulator leads short, then solder 25mm lengths of medium-duty hookup wire to the stubs, using some small diameter heatshrink tubing to insulate the solder joints and the lead stubs.

You can then solder these three leads to the regulator pads on the PCB, ensuring that it is soldered the right way around - ie, so that if you hold it up above the board with the wires not crossing over, the tab is facing away from the board as shown in Fig.5.

Early testing

Now you can apply 12V power to DC input connector CON1 and make some checks. Unfortunately, there is no power-on indicator LED at this stage (there will be when MOD1 is fitted), so the simplest check is to measure the voltage at the right-hand pin of JP1 relative to a ground point such as the mounting screw hole in the middle of the board. At this stage, there should be little to no voltage yet.

Now briefly press power switch S3, and you should measure close to 5V on the right-hand pin of JP1. Press S3 again and that voltage should drop away to almost zero. That confirms that the power supply section is working correctly.

Modifying the AD9850 module

Minor modifications are required to the AD9850 module before mounting it on the PCB. Three SMD resistors need to be removed and a thin wire soldered to one of the free pads. These changes are shown in Fig.6 and the accompanying photo of the modified module.

The module I used is, I believe, the most common version but there appear to be other versions available that use the same circuit but a different layout.

So if your module does not look exactly the same as mine, don't panic!

You can use a DMM set on continu-

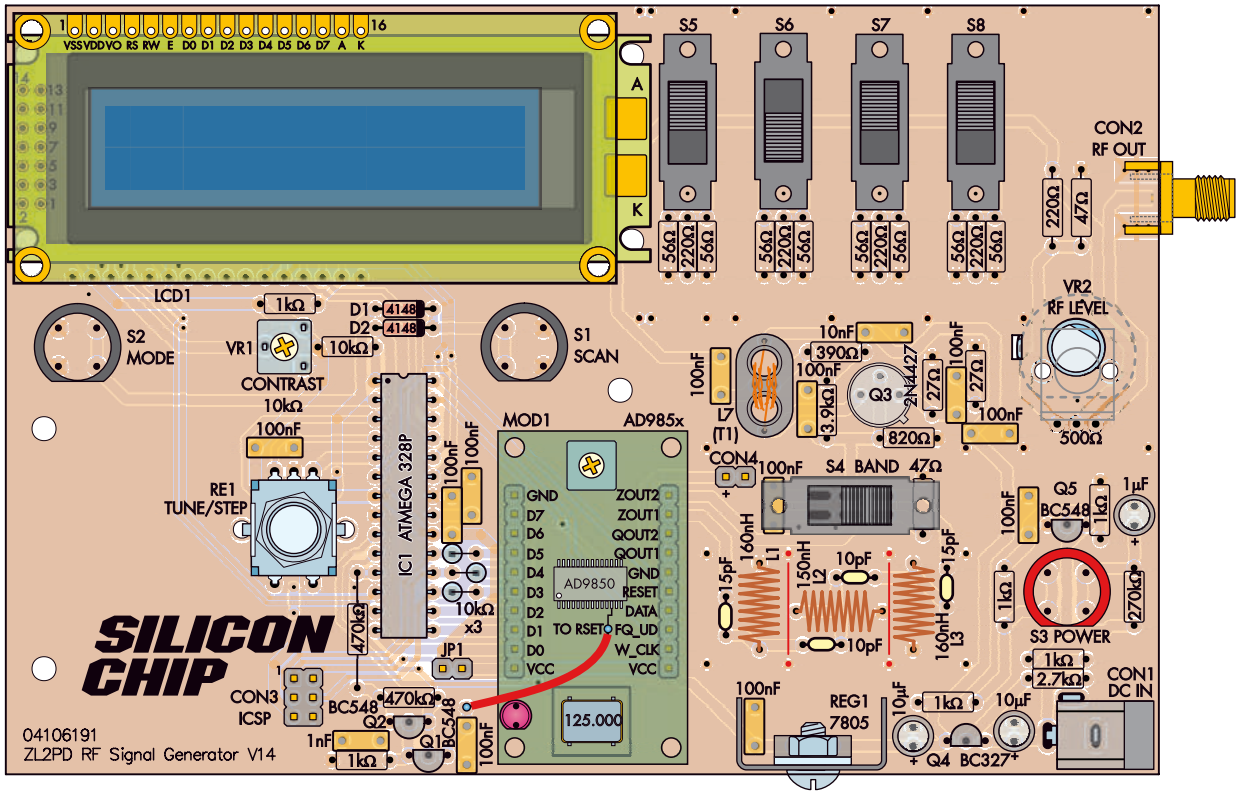


Fig.5: use this overlay diagram as a guide to building the Signal Generator. We've shown both LCD screens in place here, (Jaycar QP5516 and Altronics Z7013; one on top of the other) but you would only fit one or the other. Edge connector CON2's middle pin is soldered on the underside of the board. VR2 can be a standard 16mm pot mounted through the board, with the body on the underside, or a 9mm vertical PCB-mounting type.

ity mode to identify the resistors connected to pins 3, 4 and 12 of the IC and then remove them.

You can do this by heating the ends of the resistors alternately with a soldering iron while holding the body of the resistor with tweezers. Once enough heat has been applied, you can lift it right off the board.

If you have a hot air rework station, that makes it even easier.

It's then just a matter of soldering a 100mm length of light-duty hookup wire, or Kynar (wire wrap wire) to the now-empty pad which connects to pin 12 of the IC, as identified in the photo. This will be soldered to the main board later.

Winding coils L1-L3

The three inductors, L1-L3, are wound with 0.8mm diameter (26 gauge) enamelled copper wire. These are air-cored, meaning the coils are first wound around a suitably sized former, then the former is removed.

The coil diameters should all be 3mm, so a 3mm drill bit shaft or 3mm diameter metal tube would be suitable. The coil is then self-supporting when mounted on the PCB.

L1 and L3 need to be 160nH while L2 is 150nH. To achieve this, wind 11 turns for each coil, but then stretch L2 so that it is around one millimetre longer than the other two. That reduces its inductance to the required value.

(You could, of course, use an inductance meter to verify the coils if you have one).

If you want to achieve the alternative inductor values mentioned last month, reduce the number of turns to six, then stretch L2 by around half a millimetre.

Now remove the enamel at each end of the remaining wire on each coil. Some enamel coatings vaporise while being tinned, but most must be scraped off with a sharp knife.

Take care if you use the latter approach, especially to avoid cutting yourself. You can verify that you've scraped off the insulation properly by tinning the wire ends and then checking that the solder has adhered.

But note that you don't want a lot of excess lead length on these coils; just enough to make it through the mounting holes on the PCB and be soldered on the underside.

So cut the wire ends to length before stripping the enamel.

Don't stretch or compress the coils to fit the pads on the PCB as this will affect their inductance; just use a short length of extra wire at one or both ends to reach the mounting pads.

Winding the transformer

T1 is wound on a 14mm-long ferrite balun core. Begin with 400mm of 0.315mm diameter (28 gauge) enamelled copper wire.

Fold the wire in half so the two cut ends meet, then twist the two wires together to produce a twisted wire similar to that shown in Fig.7.

It can have anywhere from one to five twists every 20mm; this isn't critical. Twisting the wire simply makes winding the wire onto the core a little easier.

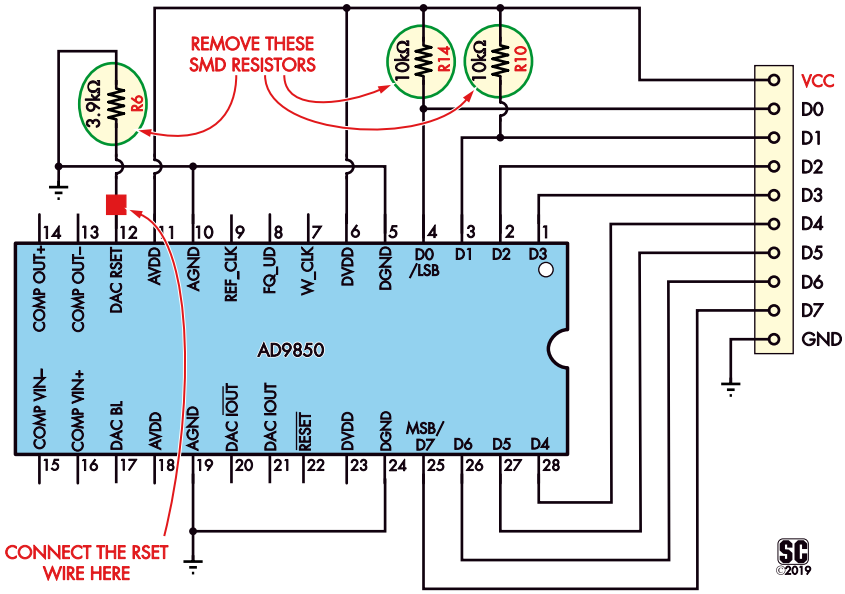
Wind four turns of the twisted wire onto the core and trim the ends of the 'bifilar' wires, so you have four short lengths of wire each about 20mm long appearing at one pig-nose end of the core.

Tin these four ends. Use a multimeter to identify the start and end of the two coils.

The start of one coil and the end of the other (shown as 'AS' and 'BF' in the diagram) go to the two central mounting pads for T1 (either together into one pad, or separately into each), while the other two wires go to the mounting pads at either end.

It doesn't matter which goes to which, as the coil is symmetrical.

Again, cut the leads to leave just a minimal amount and then strip the enamel off and tin them before solder-



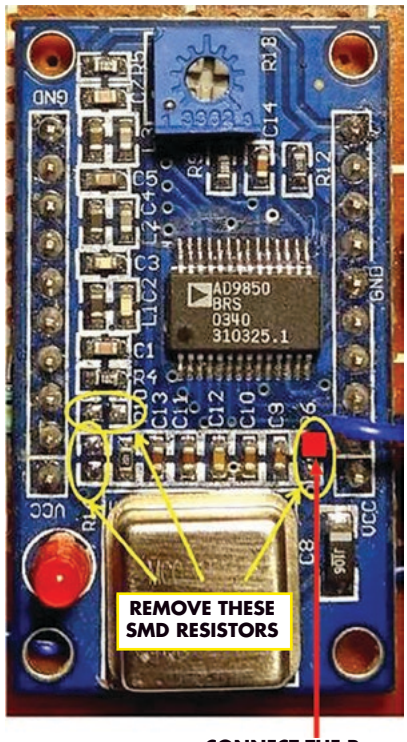


Fig.6: these three SMD resistors must be removed from the AD9850 DDS module. One of the pads which connected to the now-gone 3.9kΩ resistor makes a handy connection point for the extra wire needed to connect pin 12 of the IC (RSET) to the collector of transistor Q1 on the main board, for output level control. See also the close-up photo at right.

ing them to the board.

This should allow you to mount the balun close to the board, so it won't rattle around after the wires are soldered.

Proceeding with construction

Now fit metal can transistor Q3 close to the PCB, leaving about 1mm between the bottom of the device and the upper PCB surface. Don't install it firmly down on the PCB because the metal case of the transistor is internally connected to the collector terminal of Q3.

Also, before you solder it in place, check the metal case is not touching any adjacent component leads.

Next, fit your modified AD9850 DDS module by soldering two 10-pin headers to the PCB, then soldering the module to the pins on top of these headers.

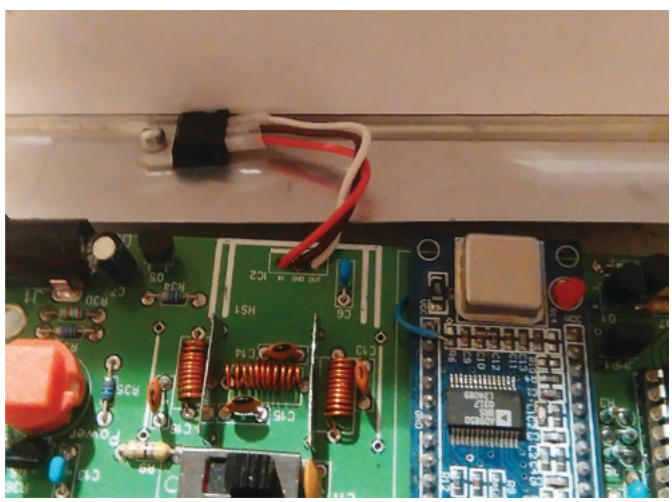
The wire you connected to that module earlier connects to the lead of transistor Q1 which is closest to MOD1. RevB PCBs have a dedicated pad for this wire.

Otherwise, solder it directly to Q1's lead, on the top side of the PCB. Either way, trim the wire to length before stripping and soldering it. This wire should ideally be routed under the module for neatness. If you keep it short, it won't move around later.

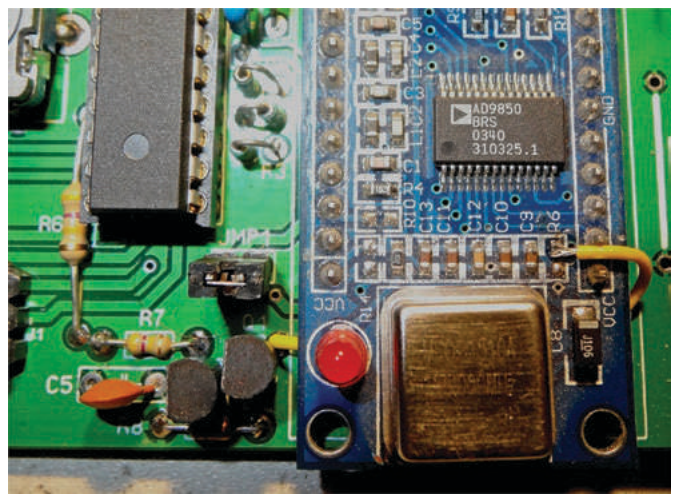
Next, fit output socket CON2. As it's an edge connector, push it onto the edge of the PCB, with the central pin sliding over the central pad on the bottom side.

Solder that central pin, plus the posts on either side, on both the top and the bottom sides of the PCB.

As this is a fairly substantial chunk of metal being soldered to copper planes, you will need a hot iron and



Two inter-coil screens, show in red on the overlay) must be fitted between the coils as shown here. These can be cut from a scrap of tinplate (eg, a food tin). This photo also shows the mounting of the 7805 regulator on the case heatsink.



The modified AD9850 module *in situ* on the main PCB. The three SMD resistors are all removed and the yellow wire is soldered to the appropriate pad – the one marked R6. (make sure it is the one closest to the AD9850 IC).

be generous with the solder.

Then install mini slide switches S5-S9. The board is designed with slots to suit their lugs, so you can solder them right down onto the PCB. Again, be generous with the solder to ensure good joints.

The next job is to mount the LCD. There are three possible headers to suit different LCD module styles, although Jaycar QP5516 or Altronics Z7018 are the best fit.

For the Jaycar LCD, solder a 8x2-pin DIL header to the row of pins nearest the left edge of the PCB, then attach the four short tapped spacers to the corner mounting holes from the bottom of the board, using 5mm machine screws.

You can then slip the LCD over the pin header and attach it using four more 5mm machine screws, then solder the header pins to the top of the LCD.

The procedure for the other LCDs are similar except some LCDs may require short jumper wires to connect to the PCB.

The final two components proper to fit are rotary encoder RE1 and potentiometer VR2. Mounting RE1 is easy; make sure it's perpendicular to the PCB and pushed all the way down before soldering its pins.

Solder its five pins and two mounting lugs; you will need a hot iron for the latter, and be generous with the solder.

For VR2, we've provided two different options. The prototype used a 16mm potentiometer with its body on the underside of the PCB and its shaft passing up through a hole.

Mounting it in this way is a bit fid-

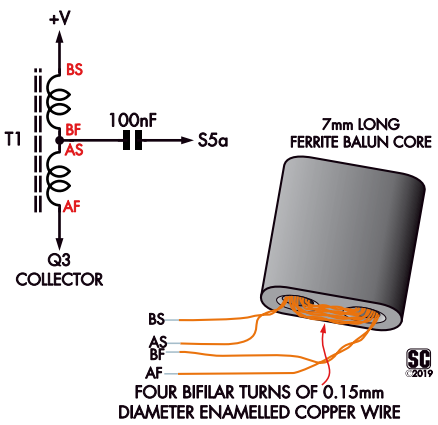


Fig.7: autotransformer T1 is easy to make, with just four bifilar turns wound on the small ferrite balun core. AF and BS are interchangeable and are connected together on the PCB.

Parts list – HF/VHF RF SIGNAL GENERATOR

1 double-sided PCB, coded 04106191, 152.5 x 102mm
1 AD985x-based DDS module (MOD1)
1 PCB-mount barrel power socket (CON1)
1 SMA edge-mount socket (CON2)
1 2x3 pin header (CON3)
2 2-way pin headers (CON4)
1 jumper shunt/shorting block (JP1)
1 16x2 alphanumeric LCD with backlight (LCD1)
[eg, Jaycar QP5516 or Altronics Z7018]
1 500mm length of 0.8mm diameter enamelled copper wire (for winding L1-L3)
1 400mm length of 0.315mm diameter enamelled copper wire (for winding T1)
1 7mm ferrite balun core (for T1) [Jaycar LF1222, Altronics L5235]
1 PCB-mount vertical rotary encoder with integral switch (RE1) [Jaycar SR1230]
1 28-pin narrow DIL socket (for IC1)
2 10-pin headers (for mounting MOD1)
1 16-pin SIL or 8 x 2 DIL header (for LCD)
4 6.3mm long M3 tapped Nylon spacers (for LCD)
8 5mm M3 panhead machine screws (for LCD)
2 black PCB-mount momentary pushbuttons (S1,S2)
[eg Jaycar SP0721, Altronics S1096]
1 red PCB-mount momentary pushbuttons (S3) [Jaycar SP0720, Altronics S1095]
5 DPDT mini slide switches (S4-S8) [Jaycar SS0852, Altronics S2010/S2020]
1 9mm diameter knob to suit VR2
1 28-34mm diameter knob to suit RE1
1 0.5mm thick tin plate or cleaned tin-plated steel cans (eg, a large Milo tin lid)
2 0.8mm thick aluminium sheets, 300 x 250mm
1 adhesive panel label, 157 x 107mm
4 small self-adhesive rubber feet
Hookup wire, misc. enclosure hardware

Semiconductors

1 ATmega328P microcontroller programmed with 0410619A.hex, DIP-28 (IC1)
1 7805 5V 1A linear regulator, TO-220 (REG1)
3 BC548 NPN transistors, TO-92 (Q1,Q2,Q5)
1 2N4427 NPN RF transistor, TO-39 (Q3)
1 BC327 PNP transistor, TO-92 (Q4)
2 1N4148 small signal diodes (D1,D2)

Capacitors

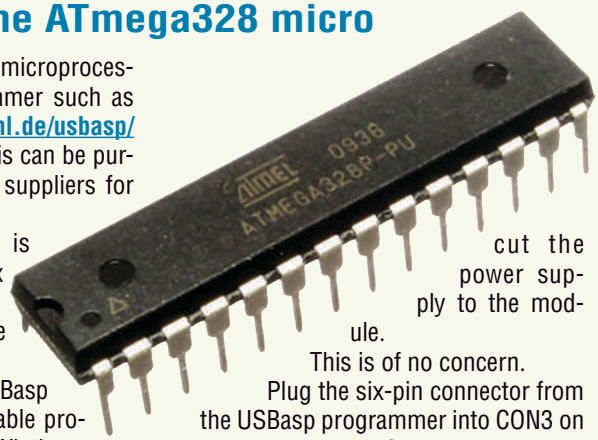
2 10µF 50V electrolytic
1 1µF 50V electrolytic
11 100nF 63V MKT
1 10nF 63V MKT
1 1nF 63V MKT or 50V ceramic
2 15pF 50V C0G/NP0 ceramic
2 10pF 50V C0G/NP0 ceramic

Resistors (all 0.25W 1% metal film)

	4-band code		*5-band code*
2 470kΩ	*yellow violet yellow brown*	*or*	*yellow violet black orange brown*
1 270kΩ	*red violet yellow brown*	*or*	*red violet black orange brown*
4 10kΩ	*brown black orange brown*	*or*	*brown black black red brown*
1 3.9kΩ	*orange white red brown*	*or*	*orange white black brown brown*
1 2.7kΩ	*red violet red brown*	*or*	*red violet black brown brown*
6 1kΩ	*brown black red brown*	*or*	*brown black black brown brown*
1 820Ω	*grey red brown brown*	*or*	*grey red black black brown*
1 390Ω	*orange white brown brown*	*or*	*orange white black black brown*
5 220Ω	*red red brown brown*	*or*	*red red black black brown*
8 56Ω	*green blue black brown*	*or*	*green blue black gold brown*
2 47Ω	*yellow violet black brown*	*or*	*yellow violet black gold brown*
2 27Ω	*red violet black brown*	*or*	*red violet black gold brown*

1 10kΩ mini horizontal trimpot (VR1)
1 500Ω 9mm vertical PCB-mount or 16mm standard potentiometer (VR2)

Programming the ATmega328 micro



To program AVR family microprocessors, you need a programmer such as the USBasp (see www.fischl.de/usbasp/ for details and drivers). This can be purchased online from many suppliers for just a few dollars.

Suitable free software is available for Windows, Linux and Apple IOS online. This description will focus on the Windows version.

You need to install the USBasp drivers and download suitable programming software. For Windows, this includes

eXtreme Burner (http://extremeelectronics.co.in/avr-tutorials/gui-software-for-usbasp-based-usb-avr-programmers/),

AVRDUDESS (http://blog.zakkemble.net/avrdudess-a-gui-for-avrdude/) and

Khazama (http://khazama.com/project/programmer/).

Plug it in and complete the installation of the USBasp programmer into your PC. If you have the option of 3.3V or 5V programming levels, select 5V.

Launch the programming software you downloaded earlier and set the target device to "ATmega328" or "Atmega 328P", depending on your chip. Both may be used. Now download the HEX file for this project from the SILICON CHIP website (if you don't already have it) and select it as the file to be used to program the chip in your software.

Make sure JP1 has not been fitted to your signal generator board; if it has, remove it now. Note that since some of the ATmega328 pins connect to the AD9850 module, the AD9850 module's power LED will still light up and flash while the programmer is connected and running, despite having removed JP1 and therefore cut the power supply to the module. This is of no concern.

Plug the six-pin connector from the USBasp programmer into CON3 on the signal generator PCB, making sure that pin 1 on the programmer cable lines up with the pin 1 indicator on the PCB.

Now select "Write FLASH buffer to chip" or "Write – Flash" to program the ATmega328 with the HEX file. The LEDs on the USBasp will blink furiously for a minute or two while the HEX file is loaded into the ATmega328. A bar graph may be displayed in some cases on the PC screen, to show progress.

You then have to program the ATmega328 internal 'fuses'. These configure the operating characteristics of the ATmega328 to suit the software being run on the device.

For this step, insert the following settings into the relevant Fuse page/section of the programming software, then click on "Write" to send the data to the fuses:

Low byte: 0xE2
High byte: 0xD9
Extended byte: 0xFF
Lock byte: 0xFF

Since the processor and display are powered via the programmer, once programming is complete, the display will briefly show the start-up message and then the initial signal generator screen. At this point, you can unplug the programming cable from CON3 and place a shunt on JP1.

dly, but there are two benefits: this is a standard part that's easier to get, and its shaft will line up perfectly with pushbuttons S1/S2 and the access hole for trimpot VR1 (if provided).

Alternatively, if you can get your hands on a 9mm PCB-mounting right-angle potentiometer, it will be dead easy to mount to the PCB, as it's fitted similarly to RE1.

However, due to the location of the hole for the 16mm pot's shaft, its shaft will sit around 3.5mm lower than S1/S2 and VR1.

But this is hardly a tragedy. So the choice is yours.

Now plug in the ATmega328 microcontroller (IC1), making sure its pin 1 is orientated correctly, to towards the upper-left corner of the board.

If you haven't already programmed it or purchased a programmed chip, see the panel above detailing the programming instructions.

Further testing

Later, we will be attaching REG1 to the metal case but since we haven't built it yet, so for further testing, temporarily attach a flag heatsink or attach it to a spare sheet of metal using a machine screw and nut.

You can now apply 12V power to CON1, press S3 and check that you can control the output frequency, amplitude etc (see the operating instructions below).

Power the unit down before finishing construction.

Fitting the shields

You will notice several holes around the buffer, attenuator, output and band select/HPF sections of the board. There are also lines on the PCB 'silkscreen' between these holes. This is where shield plates can be fitted.

However, you do not need to fit shields in most of these areas; the only ones that are critical are those between the three high-pass filter sections (between L1 & L2 and L2 & L3).

So you only really need to cut two shield pieces and mount them using four posts in the holes provided. These are shown in red on the PCB overlay diagram, Fig.5.

Each shield piece should be around 8mm high and cut from 0.5mm tin plate, or recycled tin cans (a fruit or Milo tin lid is ideal).

The strips are then mounted to the board using component leads off-cuts soldered into the holes shown in red. This is simple yet effective.

You could fit shields in the other locations but testing has shown that it makes virtually no difference to the device's performance so I don't feel that it's worth the time and effort to do so.

Making the enclosure

I couldn't find a suitable ready-made box for the signal generator, so I came up with a relatively easy way to make one.

It's a simple folded metal box and works well, resulting in a unit that is light but robust, compact and effectively shielded.

Dimensioned drawings of the metalwork are available on the SILICON CHIP website – they're a little too large to publish here! The two panels are cut and folded from 0.8mm thick aluminium sheets. The top cover and base may each be cut from a small 300 x 250mm sheet, making it relatively inexpensive to build.

This grade of aluminium is light

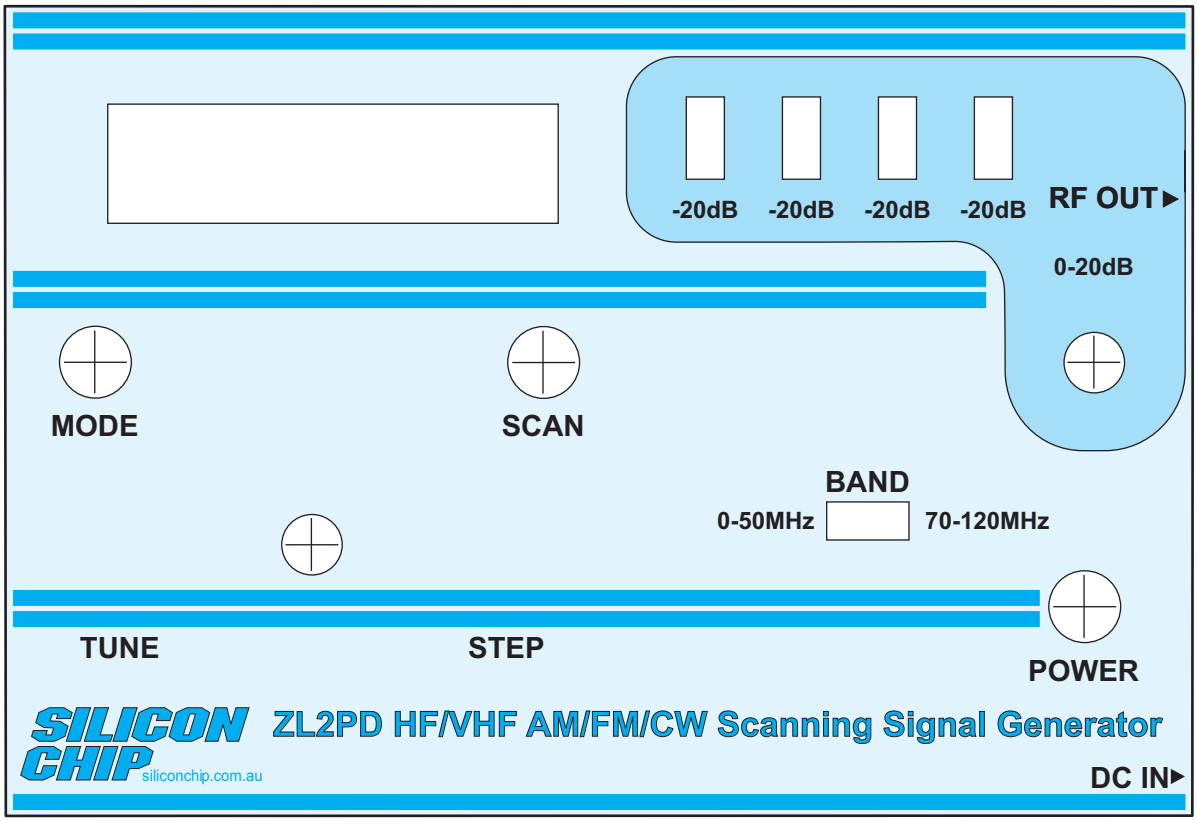


Fig.8: this panel label can be photocopied here or downloaded from the Silicon Chip website (as a PDF) and then printed. You could then laminate it, cut out the display and switch holes, then cut it to size and glue it to the outside top of the case.

enough to be cut and folded easily with hand tools, but heavy enough to form a sturdy box for the signal generator.

Several holes need to be drilled and cut into the panel for the controls, slide switches, regulator and the LCD. Aside from standard drills, a metal nibbling tool is ideal for cutting out the rectangular holes.

Final finishing during fitting can be completed with a fine file.

The completed PCB is mounted using spacers and 3mm machine screws. It's best to line it up with the holes in the lid to figure out exactly where it will sit in the case before marking and drilling out the three mounting holes in the base.

Alternately, as in the prototype, the signal generator PCB can be held onto the front panel using the rotary encoder nut, although it would probably be better to attach using at least one tapped spacer too.

Small self-tapping screws are used to hold the cover to the base of the box. Once you've cut and bent the sheets, rivet or screw the 7805 regulator (REG1) onto the metal cover just before the final step of screwing the cover to the base.

The front panel artwork is shown in Fig.8 above. This can be printed on a colour printer and covered with transparent self-adhesive plastic film.

Trim the artwork to cut out the holes for the various controls and display and test-fit onto the completed metal-work.

The most reliable method to fix the artwork in place is to spray the rear side of the artwork with adhesive spray obtainable from most stationary shops. While tacky, press the panel artwork into place. Remove the rotary encoder nut before attaching the front panel, then re-attach it on top.

3D-printed knobs

Suitable knobs may be available from normal suppliers. However, I designed the knobs for my Signal Generator using DesignSpark Mechanical and 3D-printed them from grey PLA filament.

My knob STL files can also be downloaded from the Silicon Chip website for those wishing to print their own knobs. They press into place and hold securely.

It's useful to add four self-adhesive rubber feet to the rear of the enclosure. This prevents any sharp corners of the aluminium box from scratching the bench and helps to keep the oscillator in one place on the workshop bench.

Using the Signal Generator

Briefly press power switch S3 to turn the signal generator on. The display will show a start-up message, then after a short delay, the normal screen.

If you cannot see any text on the display, adjust VR1. This sets the LCD contrast. You can see examples of the various possible displays in the first article in this series, published last month.

The display shows the current output frequency and operating mode; the generator always starts at 10.000MHz in CW (unmodulated) mode.

The display also features a frequency 'dial' which covers a 1MHz span

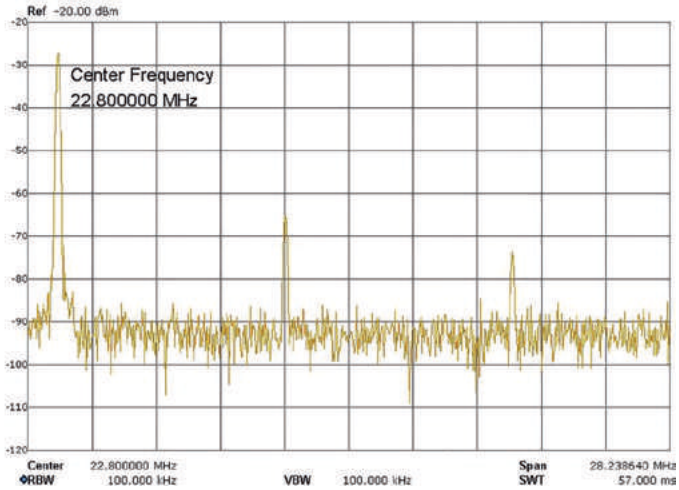


Fig.9: the CW (carrier wave, ie, unmodulated) output at 10MHz/-28dBm with a span of about 9-37MHz, selected to include the first two harmonics. This shows the second harmonic (20MHz) at around -40dB and the third (30MHz) at around -47dB.

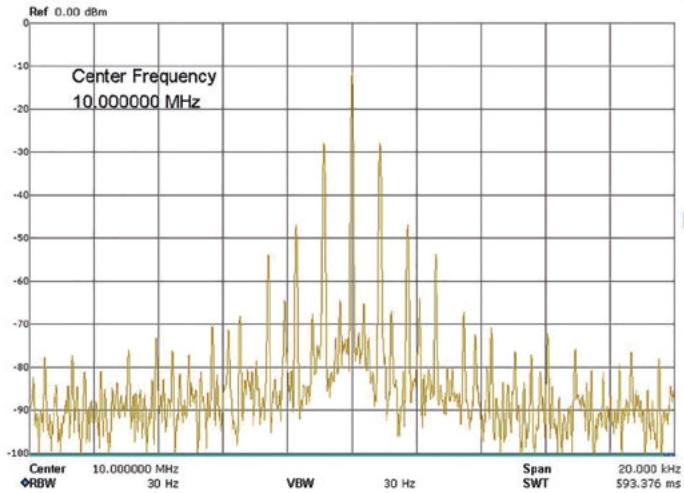


Fig.10: analysis of the AM output at 10MHz/-12dBm with a 20kHz span (ie, 9.99-10.01MHz). The 1kHz sidebands are visible either side of the carrier, as are the 1kHz modulation tone distortion products at ±2kHz (-21dB below the 1kHz fundamental) and ±3kHz (-26dB below the fundamental) indicating acceptable audio distortion levels. The modulation depth is the industry test standard, 30%.

with 100kHz markers. As you rotate RE1 ('TUNE'), the output frequency changes and the cursor on this scale shifts across the 'dial'.

Pushing RE1's knob in (the 'STEP' pushbutton) changes the increments in which the frequency is adjusted with each click as RE1 is rotated. When you push this button, the underline below the LCD frequency display moves to indicate the current step setting.

The Band switch (S4) selects between the two output frequency ranges, 0-50MHz (left) and 70-120MHz (right), while S5-S8 at the top, in combination with VR2 at right, set the output amplitude.

The Band switch must be in the correct position for the currently selected frequency to get the expected output amplitude. The HPF is very effective at minimising energy from aliasing below 70MHz, so the output level can be lower than expected by over 60dB if the incorrect selection is made.

But no damage will occur as a result of an incorrect setting.

While the upper range is described as 70-120MHz, tuning and operation are maintained up to 150MHz, although output levels fall significantly above 120MHz.

The maximum output of +7dBm is with S5-S8 all in the up position and VR2 fully clockwise. For each 20dB of attenuation you need, switch one of S5-S8 into the down position (it doesn't matter which). Then for fine attenuation adjustments, rotate VR2.

For example, if you want -30dBm, set any one of S5-S8 down (+7dBm - 20dB = -13dBm) and then VR2 should be set quite low, to give an additional 17dB of attenuation. (Note standard DDS amplitude rolloff impact above 30MHz – see Fig.3 in part 1.)

The signal generator mode is selected with brief presses of the Mode key (S2).

This selects between CW, AM, FM-NB (±1.5kHz deviation), FM-WB (±3kHz deviation), FM-BC (±50kHz deviation), or SCAN mode.

Pressing the Mode key again will select the initial CW (unmodulated) mode, again along with the standard display screen.

Frequency scanning mode

If the SCAN mode is selected, the display changes to show the currently saved Start and End frequencies for the scan, and the number of steps selected. At power-on, this is set to 200 steps. If this is the first time after power has been applied, the default frequency settings (starting at 1MHz and ending at 30MHz) are shown. Otherwise, the last used settings will be displayed.

Pressing the Scan button again allows each parameter to be selected for adjustment.

Use the TUNE and STEP controls to set the Start and End frequencies in turn; here, the STEP button selects the tuning step as usual.

When the scan Steps parameter is selected with the SCAN button, the TUNE control has no effect but pressing the STEP button allows the number of steps to be selected (10, 20, 50, 100, 200 or 500 per scan).

Finally, pressing SCAN again saves the selected values and starts the scan. The display now reports SCAN instead of the number of steps.

The scanning frequency increment is calculated by the processor using the entered values. The scanning speed is surprisingly fast.

Scanning may be interrupted and restarted using the SCAN key. When stopped, the Start and End frequencies, as well as the number of scan steps, can be adjusted again, and the scan restarted.

To exit the scan mode, press the MODE key. This also stops the scan and resets the signal generator to the last scanned frequency, and CW mode.

At each stage, the output can be checked with a suitable oscilloscope or with other RF test instruments.

Performance

Typical output signals from the Generator are shown in Figs.9-12. These were captured using a Siglent 3GHz spec-

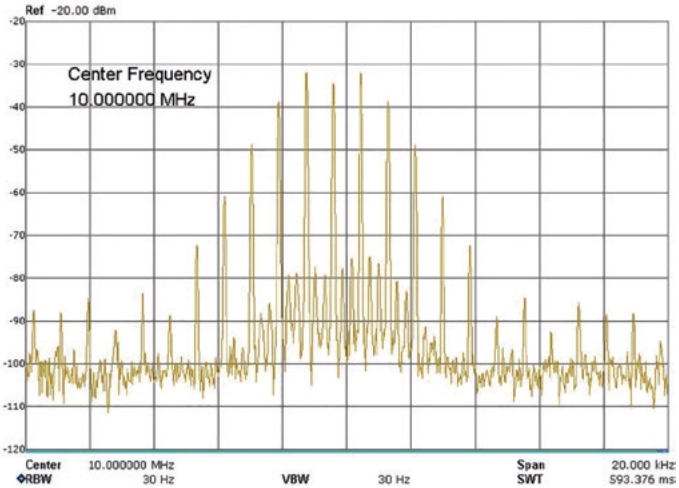


Fig.11: a "narrow band" 1.75kHz frequency modulated signal with a 10MHz carrier and a 20kHz span. The iconic equi-spaced 1kHz sidebands of a standard FM signal are clearly visible.

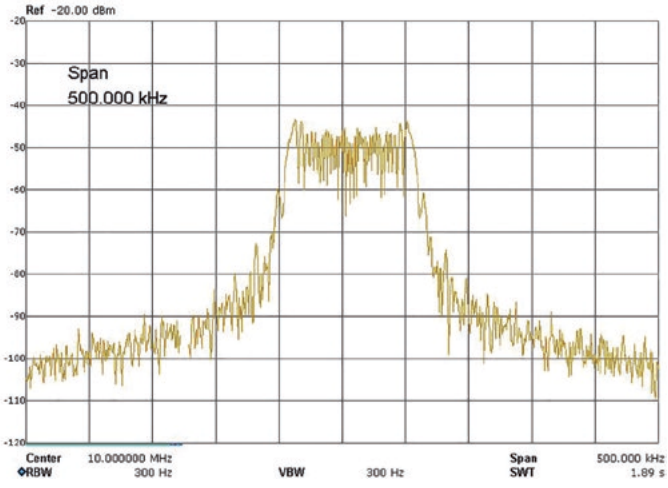


Fig.12: "wideband" or broadcast radio style FM, again with the carrier at 10MHz, this time captured with a 500kHz frequency span. This clearly illustrates that most of the signal energy falls within the 200kHz channel bandwidth permitted for broadcast FM signals.

trum analyser. See the figure captions for details.

Fig.13 demonstrates how effective the high-pass filter is, despite being made from self-wound air-cored inductors. This shows that the filter provides 60dB of attenuation for signals below 40MHz with a virtually flat passband from 70MHz up. The filter roll-off is quite steep at around 75dB/octave (the span from 40MHz to 70MHz is about 0.8 octaves).

Future possibilities

It is possible to add further features to the software. With the supplied software, less than 30% of IC1's program memory is used.

For example, RF output levelling would be possible, by using the pin 11 PWM output which drives the RSET pin of the AD9850 module (currently used to provide AM) to offset the sinX/X roll-off for frequencies up to about 50MHz, at the cost of a reduced maximum output level at lower frequencies.

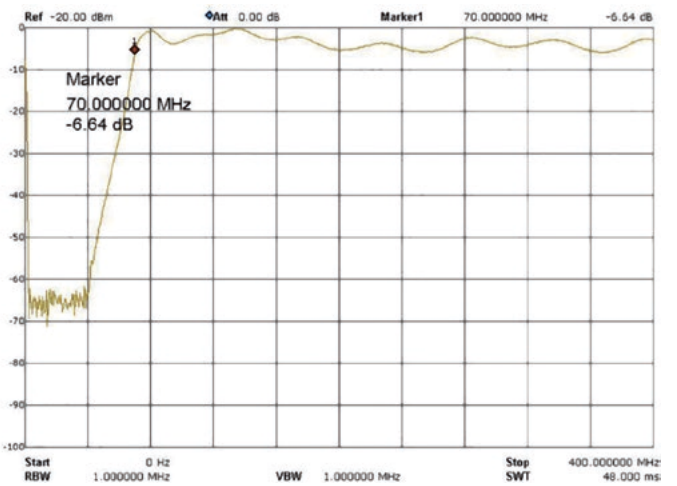


Fig.13: measured performance of the high-pass filter comprising inductors L1-L3 and four small ceramic capacitors. As you can see, the response is pretty much flat from 70MHz to 400MHz, but signals from 0-40MHz are attenuated by 60dB. The transition is smooth and quick, at around 75dB/octave, or 2dB/MHz.

Extended frequency coverage also appears possible through the use of alternative high-pass filters and/or by replacing the AD9850 module with one based on the pin-compatible AD9851.

Some minor additional software changes would be required to permit the AD9851 to be used. The AD9851 can be clocked at up to 180MHz, which may allow the generator to operate up to 100MHz in a single range, and possibly up to 300MHz with a modified HPF. Suitable AD9851 modules are available from the same sources as the AD9850-based module.

Adding other modulation modes such as FSK and BPSK is also feasible, but adding QPSK, for example, may be beyond the reach of this design.

Moving to an even more advanced DDS device, such as one based on the more modern AD99xx series chips,could be done. However, this would substantially increase the overall cost and complexity of the device.

It is also possible to replace the basic passive output variable attenuator network with a more elegant PIN diode based system.

This involves using components that are more difficult to obtain, but sufficient space has been left in this area of the PCB for such an addition.

Finally, you could consider adding a numeric keypad on the front panel to permit the direct entry of frequencies, tuning step and scan settings, plus you could add a settings memory for frequently used configuration.

However, this would likely require a processor change, or potentially even an additional microcontroller for handling keypad entry, to obtain the necessary spare I/O pins.

Having said all that, the design as presented is a good compromise between low complexity and cost, while still having a useful frequency range and a good set of features. It makes a great entry-level RF signal generator – a "must" for anyone interested in radio at any level! SC

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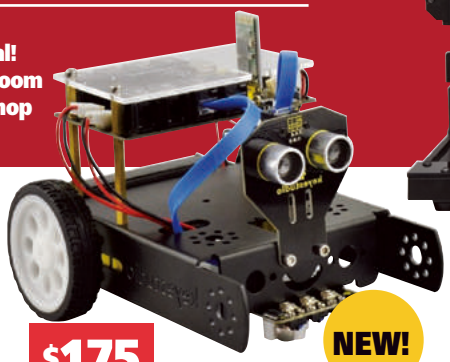

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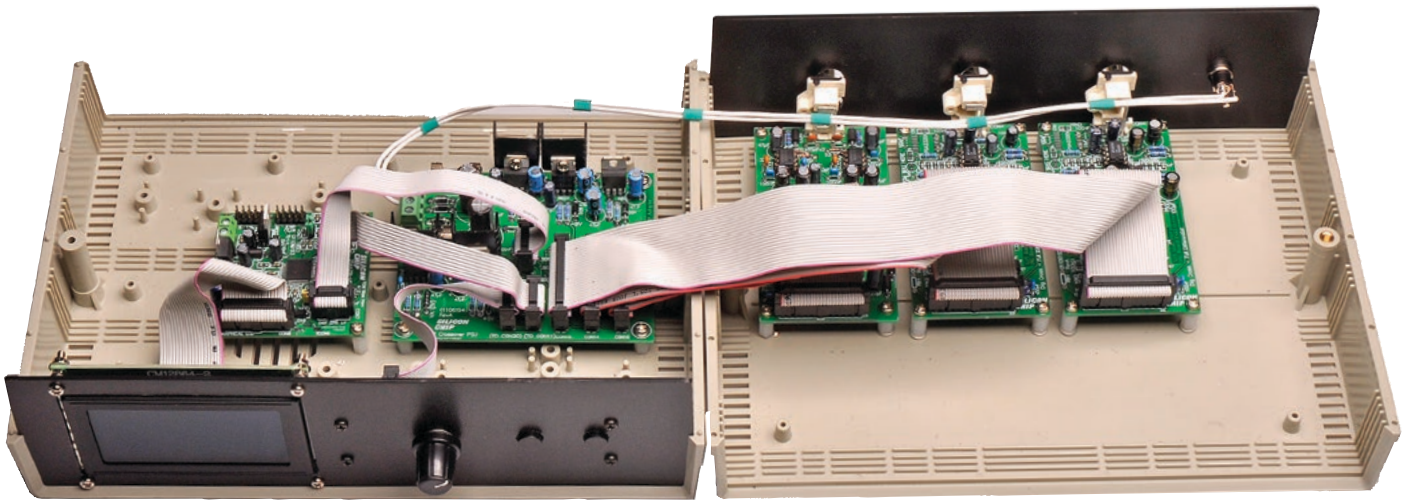
In this third article, we test the DSP Crossover modules, then finally connect them together and power the whole unit up. Once it has been tested and assembled into its case, you can then set it up before hooking it up between your preamplifier and power amplifier(s), so that it can process the sound as required.



DSP Active Crossover and 8-channel Parametric Equaliser

As mentioned in the previous articles, this DSP Active Crossover is built from six different modules: a power supply/signal routing module, a CPU board, an analog-to-digital converter (ADC) board, two identical digital-to-analog converter (DAC) boards, a front panel control board and a graphical LCD with a small adaptor so that it can connect directly to the CPU board.

Those previous articles described how the circuits of each module worked and how they join together. We also gave the assembly instructions for all the aforementioned modules.

So if you've been reading along and working as you go, at this stage, you should have a complete set of modules, but you will not have connected any of them together or applied power yet.

So now we get to the fun part: powering everything up, plugging the modules together, and seeing if it works (fingers crossed!).

Once we've verified that everything is working, we can mount all these modules in a case and then we'll explain how to use the resulting device and what sort of performance you can expect from it.

Testing

The first thing to check is that the power supply board is working properly. Regardless of whether you are planning to power the final unit using a plugpack or mains transformer, the easiest way to test it is by wiring a 12V AC plugpack to CON13 on the power supply board, either between pins 1 & 2 or pins 3 & 4.

Don't plug anything else into this board for now.

If you don't have such a plugpack, mount the mains transformer, mains input socket and fuseholder in a metal case (it's usually easiest to place these all in one corner).

Complete and insulate all the mains wiring before powering it up, and ensure that the metal case is Earthed directly back to the mains input socket or cord.

If using a captive mains power cord, ensure it is adequately clamped to the case using a cord grip grommet or P-clamp, so that pulling on the cord won't allow any internal conductors to come loose.

Part III – Design by Phil Prosser . . . Words by Nicholas Vinen

An alternative to mounting the unit in the plastic case, as seen opposite, is to use a 19-inch rack mounting case – here seen with a brushed aluminium front panel for a really professional appearance.

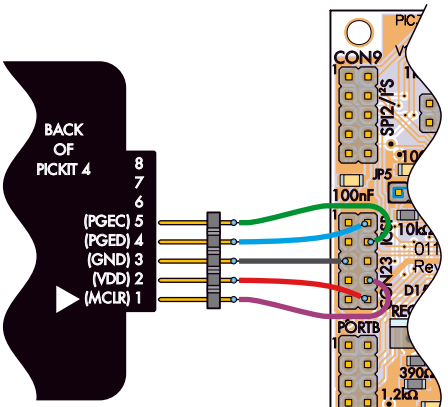


Fig.16(a): how to connect a PICkit to program the CPU using hook-up wire or patch cables. Note that the PICkit is upside-down so that pin 1 is at the bottom. Keep the wires short, or programming may fail.

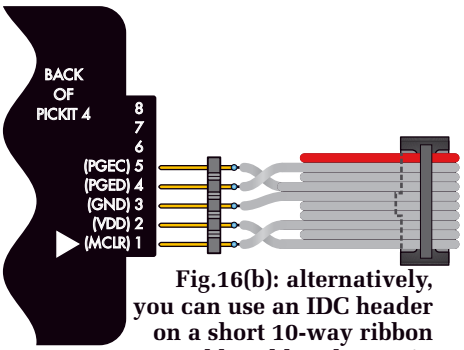


Fig.16(b): alternatively, you can use an IDC header on a short 10-way ribbon cable soldered to a pin header for programming.

Fit a fuse with a rating as recommended for the transformer you are using. This may be around 1A, or possibly slightly more if using a toroidal transformer, as these can have a higher inrush current when power is first applied.

During the following testing steps, if using a mains power supply, ensure that you can't come into contact with any of the mains conductors while probing the board.

Set your multimeter to a low DC volts range (eg, 20V). Before applying power, check the markings on the board to see where you will be probing. The right-hand end of the 0Ω resistor/wire link below D26 is a convenient place to connect your black ground probe.

You will be checking the voltages at the +9V, -9V, +5V, +3.3V, and VA (5V) pads, as indicated in Fig.11 on page 83 last month, and the PCB itself. These voltages can vary slightly from those indicated.

The acceptable ranges are: 9.2-10.4V (±9V), 4.7-5.4V (+5V, VA) and 3.15-3.6V (+3.3V).

There is no visible indication when the power supply board is powered up. As soon as you have applied power, check the DC voltages at each of the above points.

If any of these are wildly off, check the AC voltage(s) being applied to CON13 and ensure that they are not too far from the nominal 12V. The transformer being lightly loaded at this time, readings of 13-14V would not be surprising.

Note that because of the resistor values used to set the regulator output voltages, and since there is no current being drawn from the power supply as yet, it is possible that the regulated rails may be even higher than the ranges above suggest.

That's because the worst-case minimum load requirements of the regulators are not catered for with the other boards unplugged.

So if any of the expected readings are below the ranges specified, or well above them, then you should switch off and check for faults.

But if they are slightly too high, you can try connecting a 100Ω resistor from the test point to ground to see if that brings the reading back down into the expected range. If it does, then you can proceed.

Otherwise, start looking for soldering or component faults.

Programming the micro

Once you're confident that the power supply is working, if your micro is not already programmed, now is a good time to do that. If you have a

Programming with a PICkit 4 is much faster than with a PICkit 3, which is especially helpful in this project, as the HEX file is rather large – 2MB.

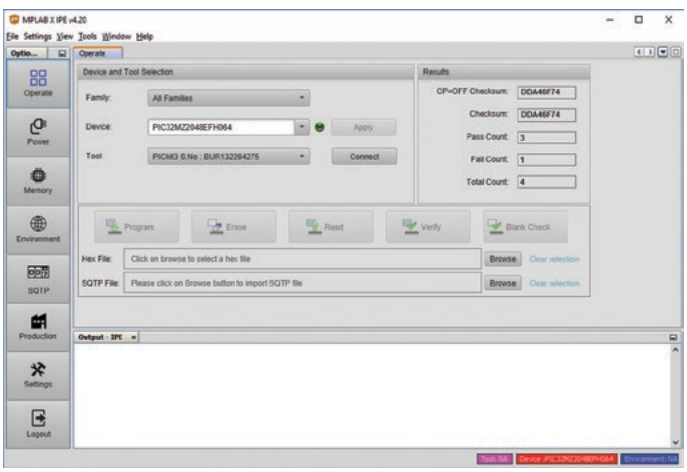


Fig.17: the first step to set up MPLAB X IPE is to select the correct PIC chip, as shown here, and check that it has detected your programmer.

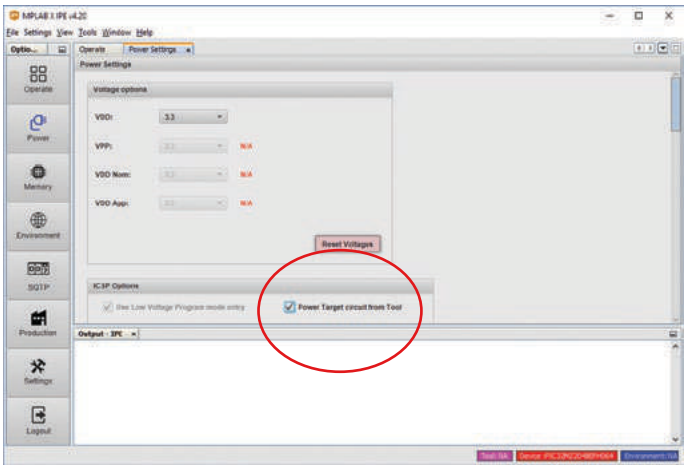


Fig.18: to make things easier, rather than powering the board externally, the PICkit can supply power to IC11 during programming, as long as you have checked this box.

PICkit 3 or PICkit 4 (or similar), you don't necessarily need to power the board up to do this; the programmer can supply power to program the chip, and indeed, it is safer to do it this way.

As mentioned last month, the programming header (CON23) does not have the same pinout as the PICkit 3/4, so you need to make up an adaptor to connect it. This could be as simple as five male/female jumper leads plugged into CON23 at one end, and the appropriate PICkit pin at the other end.

Or, you could crimp a 10-pin IDC line socket onto a spare section of 10-way ribbon cable, then separate the wires at the other end, cut some off short and solder the others to a 5-pin header. You can then plug the PICkit into that header.

To program the chip in our prototype, we soldered a 5x2 pin box header onto a small piece of veroboard, along with a 5-pin right-angle header, and then made the five required connections using short lengths of Kynar (wire wrap wire) soldered between the pads.

Regardless of the method you choose, the required cable configuration is shown in Figs.16(a) and 16(b). Remove jumper JP5 during programming and re-insert it when finished.

If using a PICkit, you can load the HEX file into the PIC32MZ chip using the free Microchip MPLAB IPE software, which is installed along with the MPLAB IDE (also a free download). Grab this from the following link: **microchip.com/mplab/mplab-x-ide**

Having installed the IPE (if you don't have it already), launch it and change the Device field to "PIC32MZ2048EFH064" (see Fig.17). If you can't find that device in the list, you need to update to the latest version of the software.

Plug in your programming tool, then select it from the list and click "Apply", then "Connect". If your tool does not support this chip, you will get a message saying so.

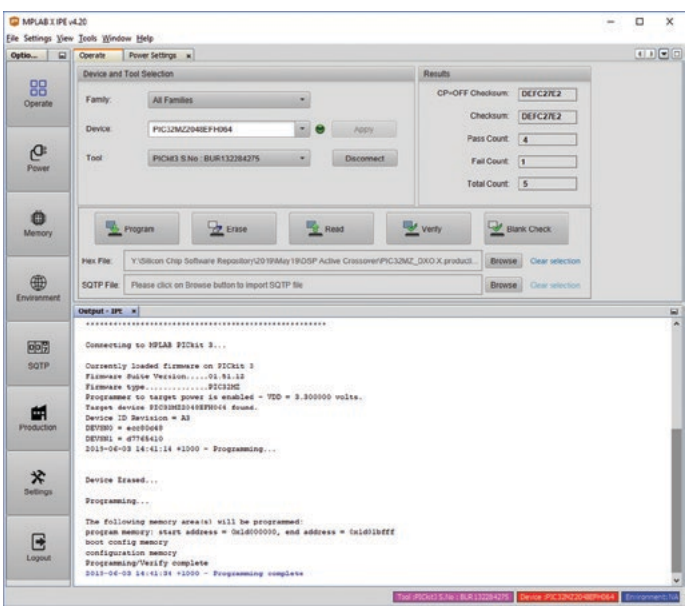


Fig.19: now we can load our HEX file, connect to the PIC and program it. If successful, you should get the same messages in the bottom pane as we did here.

You may get an error message saying that no power was detected and the connection has failed. This is fine, as we want to ensure that the PICkit is set up connectly before applying power to the chip.

Now, to the right of "Hex File": below, click "Browse" and select the HEX file which you have unzipped from the download package for this project, obtained from the SILICON CHIP website.

Next, click on the "Power" tab on the left side of the screen. You may need to switch the software to "Advanced Mode" to access this tab. Ensure that the "Power Target circuit from Tool" option is ticked (Fig.18).

Switch back to the "Operate" tab, check that your programmer is connected to the CPU board correctly (if not, click the "Connect" button again) and press the "Program" button. You will get a series of messages at the bottom of the screen indicating the progress (Fig.19).

If programming failed or you get a message that the software is unable to detect or connect to the target device, check your wiring. If that's good, then you may have a problem with the soldering of IC11 or some associated components, or you may have one or more solder bridges on the board. Examine it carefully for faults.

Our first attempt to program the chip in our prototype failed. We carefully examined all the pins of IC11 under magnification, but couldn't see any obvious problems like bridges or unsoldered pins. We solved this by adding flux paste to all the pins of IC11 and then re-flowing the solder using a hot air rework station. So that is worth trying if you can't figure out why it isn't working.

We are guessing that the solder on one of the pins on our chip hadn't flowed down onto the pad below, but it's hard to say for sure. Whatever the problem was, it's gone now.

Assuming IC11 is soldered correctly, and your programmer is wired up as shown, the chip should be successfully programmed and verified. You can then move on to the next stage of testing.

Further testing

The next step is to test the control circuitry. You will now need the three 10-wire ribbon cables you made up earlier (described at the end of last month's article). In each case, make

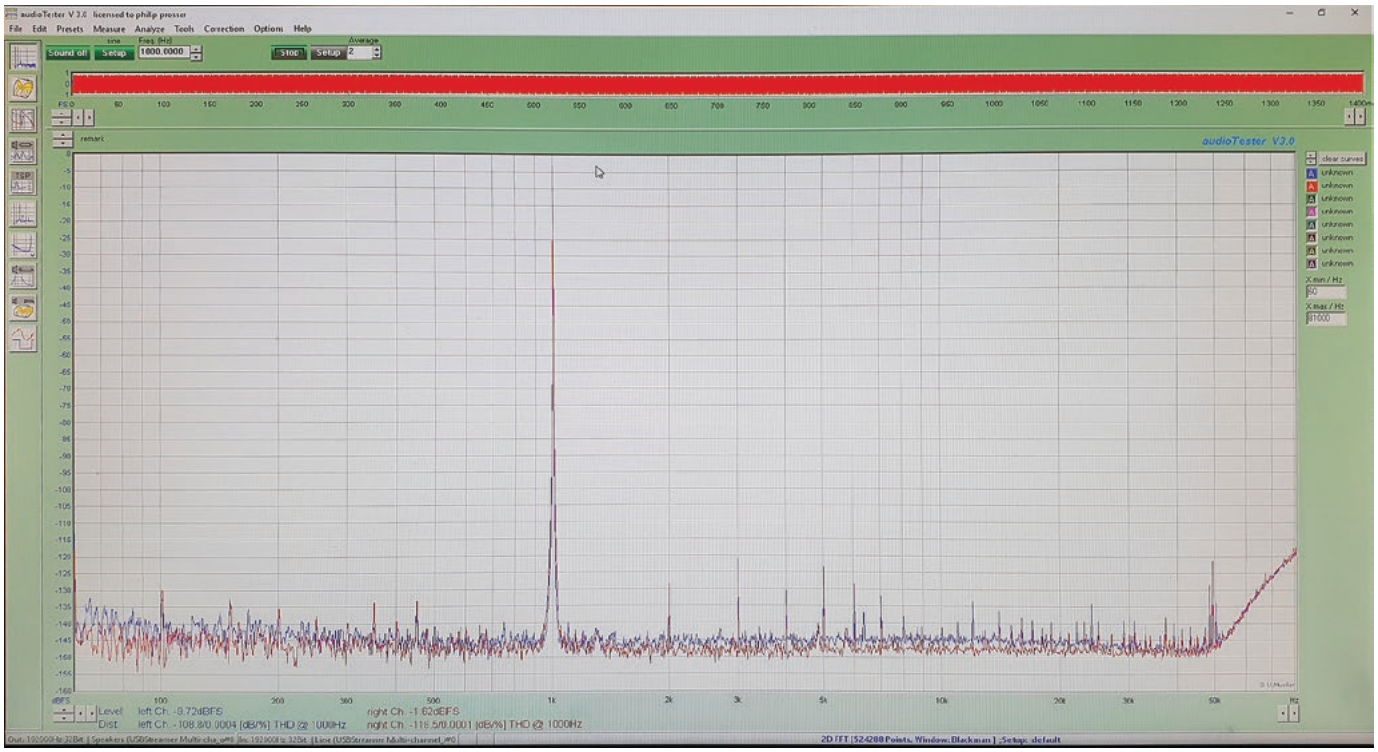


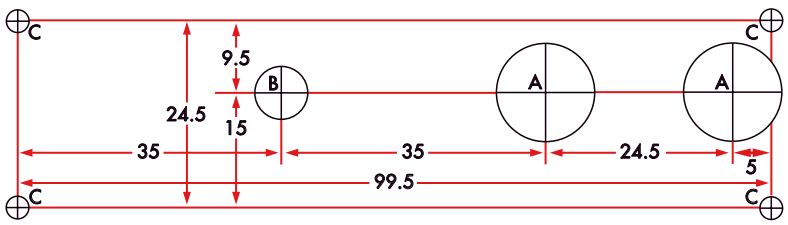
Fig.20: a PC-based spectrum analyser plot showing the output of the DSP Active Crossover when fed with a (near) pure sinewave. THD readings are shown at bottom; note that these were not done with a full-scale signal (which likely would give better results) but also, they do not incorporate noise (ie, they are not THD+N readings).

sure that the pin 1 triangle/red wire goes to pin 1 on the connector that you're plugging it into, and note that it's possible to plug in the IDC headers offset, so that some of the pins are not connected. So avoid doing that.

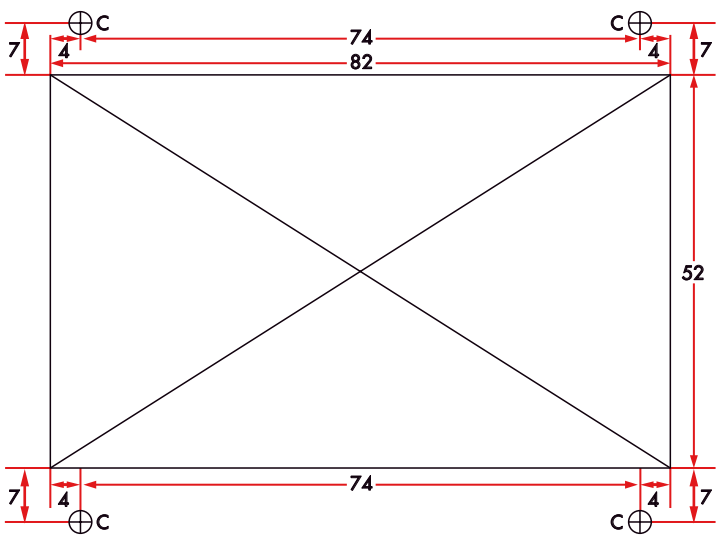
The two shorter cables connect from CON7 on the power supply board to CON17 on the CPU board, and from CON18 on the power supply board to CON11 on the CPU board. On the power supply board, pin 1 of each connector is at bottom right. On the CPU board, pin 1 of CON7 is near D16 while pin 1 of CON11 is near the 10µF capacitor.

The third, longer cable connects from CON19 on the power supply board to CON20 on the back of the front panel interface board. Again, make sure that the pin 1s are wired correctly. Pin 1 of CON20 is near to rotary encoder RE1.

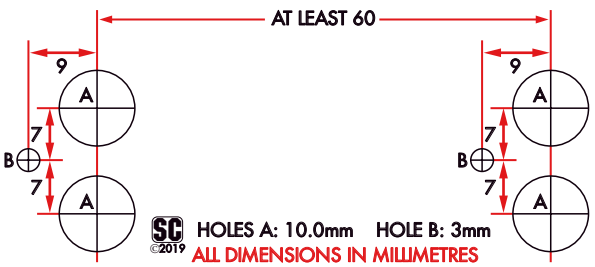
You will also need to wire up the LCD screen. This is done using the 20-way ribbon cable. Plug one end into CON8 on the CPU board (pin 1 is



HOLES A: 13.0mm HOLE B: 7mm HOLES C: 3mm ALL DIMENSIONS IN MILLIMETRES



Above left (Fig.21) are the three holes required in the front panel controls, which are all mounted on the front panel PCB – the two pushbutton switches (S1; "Exit" and S2; "Select") and the Rotary Encoder. Exact positioning on the panel is unimportant as the front panel PCB determines the position. At bottom left (Fig.22) is the cutout for the liquid crystal display, while below (Fig.23) are the four holes required for two pairs of RCA sockets (the third set would be identical but the separation may vary).

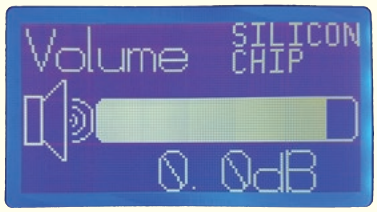


HOLES A: 10.0mm HOLE B: 3mm ALL DIMENSIONS IN MILLIMETRES

Screen01: the initial splash screen, which is quickly followed by…

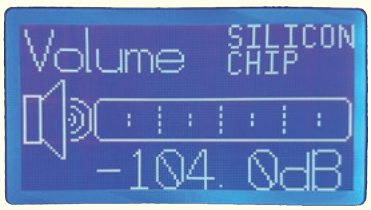
Screen02: a second splash screen, giving the software version and build date, which is then followed by…

Screen03: the default screen, which gives volume control and starts at 0dB. Rotate the encoder knob to...



Screen04: adjust the volume. If can go up as high as +12dB or down as low as…

Screen05: -104dB. Pressing either pushbutton (or the knob) on this screen takes you to…



Screen06: the main menu, which has four options. Use the rotary encoder to change the current selection and press S2 or the knob to go into that sub-menu.

Screen07: in the crossover sub-menu, first you select which band you want to adjust using the rotary encoder (you can still adjust other bands after making the initial selection).

Screen08: here we've selected Band 2. Only two bands are initially available. You need to change other settings to activate Bands 3 & 4. Selecting a band takes you to…

next to the mounting hole in the lower-right corner of the PCB) and connect the other end to the small LCD adaptor, which you will have already soldered to the back of the screen. Pin 1 is marked on that PCB.

If you don't have that adaptor, you can separate the wires in the ribbon cable and solder them to the 20 pins on the LCD screen module, with the red wire to pin 1 and so on. That's how the original prototype was built, but it's a tedious process, hence the adaptor board.

You can now apply power and check that the LCD screen lights up and you get a sensible display on the screen. You will need to adjust contrast trimpot VR1 before you see anything on the screen. Also check that LK2 is in the V_{EE} position. Turn the rotary encoder and check that you can scroll through the menus, and that pressing the front panel buttons gives the expected results.

A lack of display on the screen could be due to several problems. If you programmed the microcontroller yourself, you know that it is at least running, but there could be a soldering fault on one of the pins connecting to the LCD, or there could be a wiring problem with the cable.

LED2 on the CPU board should flicker when the display is updated, and you can force this to happen by turning the rotary encoder knob.

As the CPU board has two onboard regulators and generates its own 3.3V rail, if it doesn't work straight away, then it's a good idea to check that first. The left-hand pin of CON5, labelled GND on the PCB, makes a good reference point. There is a via between CON5 (near the GND terminal) and CON10 which connects to the +5V rail from the power supply, so check this voltage first.

Next, check the voltage on the other terminal of CON5. You should get a slightly lower reading, of around 4.7-4.8V, due to the forward voltage drop of D15. Next, to check the 3.3V rail, probe either of the vias immediately to the left of the PIC, IC11. The easiest one to reach is the one just to the right of the capacitors to the right of JP5.

Expect a reading of 3.17-3.58V. Anything outside this range suggests a problem with regulator REG2 or one of its associated components. Switch off and check the board carefully.

If the power supply rails check out, it's a good idea to verify that the primary oscillator is running. You will need a frequency meter which goes up to at least 8MHz; some DMMs have this function. Using the same ground point as a reference, probe the left-hand end of the 470Ω resistor near the bottom right-hand corner of IC11. You should get a reading close to 8MHz.

If you don't, then either IC11's oscillator amplifier is not operating (suggesting a problem with the chip, its soldering or its programming) or there is a problem with crystal X2.

If you are seeing the 8MHz signal but still not getting anything on the LCD, that suggests a connection problem between the chip and the LCD, so check all the headers and cables. If LED2 is not flickering, IC11 may not be programmed correctly or there is a bad connection somewhere, probably on the CPU board.

It's also possible that LED2 has been installed backwards. If you've verified its orientation and the chip programming, and it still isn't lighting up, check your soldering carefully.

Plugging the rest of the boards in

Assuming you have had success with the LCD and controls, you can now connect the other three boards. As

shown in Fig.6 on page 35 of the May 2019 issue, CON16 connects to CON2 on the ADC board, while CON14 goes to CON3 on the first DAC board (woofer output) and CON15 goes to CON3 on the second DAC board (tweeter output).

As with the other cables, be careful to make sure that the pin 1 side of each plug goes to the pin 1 marked for each header, and that you don't plug them in offset by one row of pins.

All the ADC and DAC boards have pin 1 on the side of the header closest to the nearest edge of the board, and similarly, on the power supply/routing board, pin 1 of each header is towards the bottom edge.

We specified three different cable lengths last month, since these three boards will be different distances from the power supply module.

In our prototypes, the ADC board is closest, so it uses the shortest cable; however, there's nothing to stop you from using a different arrangement.

Once those are all plugged in, check that JP1-JP4 are inserted and that LK1 is set to SDO4. The only way to really test it is to connect a signal source to the ADC inputs, power the unit up and check that you're getting appropriate signals from the four outputs, using either a scope or a power amplifier and speakers.

If using an amplifier, turn the volume down initially in case there's something wrong; otherwise, your ears may get blasted!

If you don't get the expected result, check that all the jumpers are in the correct positions (see last month).

Preparing the rear panel

The steps for final assembly are: drill and cut holes in the front and rear of the case, determine the ideal location for each module and mount them to the case, attach the LCD and control board to the front panel and then complete the wiring.

On the rear panel, you will need to drill six holes of 9-10mm diameter for the RCA sockets. Ideally, you should also drill a 3mm hole for each pair of RCA sockets, to mount the connector to the rear panel so that it isn't damaged when pushing the plugs in. The hole pattern required is shown in Fig.23.

Each group of holes will need to be at least 60mm apart, to give room for the boards to fit side-by-side. You may wish to increase the space between the ADC module and the two DAC modules (assuming your case is large enough), to make the distinction more obvious.

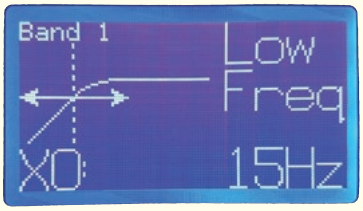
On the rear panel, you will also need to mount either a concentric socket for a plugpack or a mains cord or socket (ie, an IEC input socket).

While it's a good idea to also fit a fuseholder to the rear panel for the plugpack-powered version, it isn't strictly necessary. However, you definitely need a fuse if using a mains power supply. Our second prototype, shown in the photos here, is plugpack-powered.

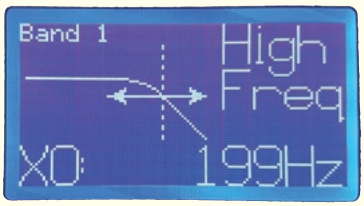
Mains wiring

For a mains supply, if you're fitting an IEC socket for convenience (wired-in or "captive" mains cords can be a bit of a pain), you can use one with an integral fuse and then you won't need to mount a separate fuseholder.

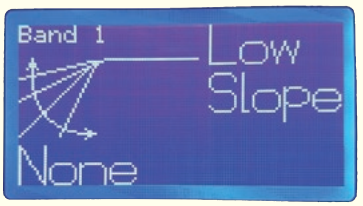
But note that IEC sockets with fuse holders often have exposed, live conductors on the inside, so it's a good idea



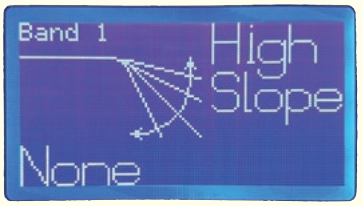
... Screen09: the first adjustment, which allows you to adjust the lower -3dB point using the rotary encoder, to as low as 15Hz. Pressing S1 will take you back to the volume screen, or press S2 to go to...



Screen10: the second crossover adjustment, the upper -3dB point, which goes as high as 15kHz. Here it is set to 199Hz. Pressing S2 takes you to…



Screen11: the lower slope adjustment. You can select None, 6dB/octave or 12dB/octave Butterworth, or 24dB/octave Linkwitz-Riley filters. Then press S2 to go to…

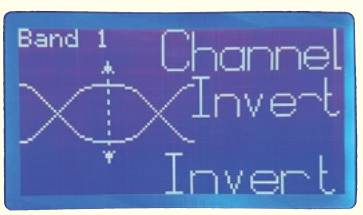


Screen12: the upper slope adjustment, where you have the same options. Press S2 again to go to…

Screen13: the delay adjustment, allowing time-compensation of drivers in a speaker cabinet. The setting (up to 6239mm) is converted to a delay based on the speed of sound. Press S2 again to go to…

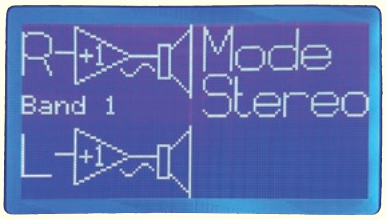
Screen14: the attenuation adjustment, which can be set from 0dB down to -20dB. It can be used to compensate for different driver efficiencies etc. Pressing S2 again takes you to…

Screen15: the option to invert the signals for this output, which may be useful if you have drivers wired out-of-phase. Rotating the knob…

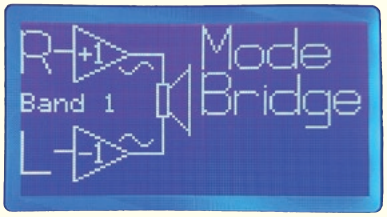


Screen16: selects inverted mode, while rotating it further returns to normal (non-inverted) mode. One more press of S2 takes you to…

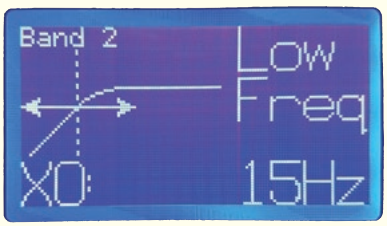
... Screen17: the crossover mode screen. By default, it's Stereo, as shown here, but you can change it to...



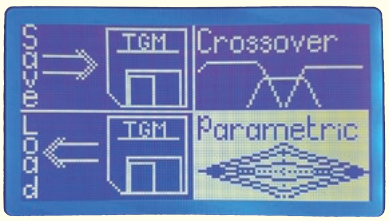
Screen18: Bridge mode, where the second output is an inverted version of the first output, for using two mono amps (or one stereo amp) to drive a speaker in bridge mode. Pressing S2 again...



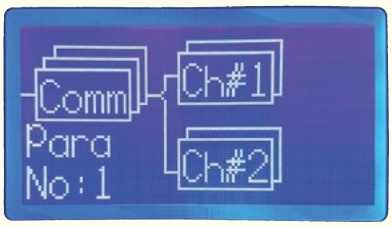
Screen19: cycles through the same set of options for the next band, starting with the lower -3dB point adjustment and then all the different settings and bands until it loops back to Band 1.



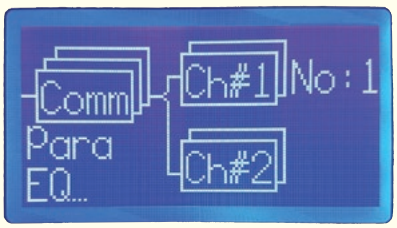
Screen20: here's the main menu again, and this time we have selected the Parametric settings. Pressing S2 takes us to...



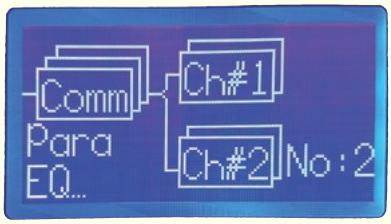
Screen21: this screen lets you choose which parametric equaliser band to adjust. There are four bands which apply to both channels, plus two that only apply to each of the two individual channels....



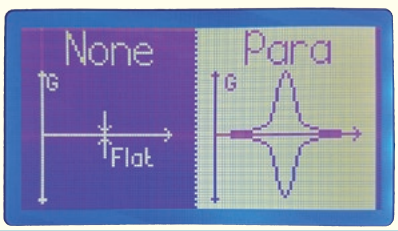
Screen22: The rotary encoder lets you select any of these eight equaliser bands. Here we have selected the first band which applies only to Channel 1, and here...



Screen23: we have selected the second band which applies only to Channel 2. Pressing S2 on any of these options takes you to...



Screen24: this screen, which lets you switch on or off each equaliser band. Pressing S2 again takes you to...



to apply neutral-cure silicone sealant in these areas so that they are not a shock hazard if you operate the device with the case open, during testing.

It is somewhat easier to drill a hole to suit a wired-in mains cable, and that is a valid approach; just make sure you fit a proper 'safety' fuseholder wired in series with the active lead, and that you provide adequate clamping to ensure the mains cord can't be accidentally pulled out, even if the unit is dropped.

The best way to do this is either using a cord grip grommet (although this does require a properly profiled hole to be made) or an appropriately sized cable gland. If using a cable gland, it's best to fit the part which tightens up around the cable on the inside of the case, so it can't be loosened from the outside. Alternatively, apply superglue (cyanoacrylate) to the threads before tightening it up.

Another thing that's necessary if you are using a mains power supply in a metal case is to properly Earth the case. Run a short green/yellow striped Earth wire (stripped from a section of 10A-rated mains cable) directly from the mains input socket to a chassis-mounting eyelet or spade lug. If the case is painted, scrape the paint away around the lug mounting point.

Use the largest diameter screw possible to attach this lug, along with shakeproof washers and two nuts. If using a captive mains cord, simply separate its Earth wire and run it to this chassis Earth lug. You do not need to make an Earth connection anywhere else in the device.

You also need to ensure that there is good electrical continuity between the various case panels when the case is assembled. This may require removing some paint where the panels are screwed together, or otherwise attached.

Verify that you have a low resistance between any exposed metal on the case and the mains Earth pin before powering the unit up.

Mounting the modules

Once you have made the holes in the rear panel and attached and wired up any required power supply components, you can mark out the mounting hole positions for the power supply board, CPU board, ADC board and DAC boards. Drill these to 3mm, deburr, then attach the modules using machine screws and tapped spacers. You can then wire them back up, as you did during the testing.

That just leaves the LCD and front panel control module to mount. You need to make a rectangular cutout 82mm wide and 52mm tall in the front panel for the LCD screen to fit through. (See Fig.22).

Make sure it's centred vertically on the panel, and at least 5mm from any protrusions on either side, as the LCD board is slightly larger than the screen (92mm x 70mm).

You can draw the required outline on the panel and then cut it out using a rotary cutting tool like a Dremel. Or you could drill a hole and then use a nibbling tool. Either way, file the edges smooth and make sure that the panel fits, then mark out and drill the four 3mm corner mounting holes. You can then attach the panel using 16mm M3 machine screws, nuts and washers.

Extra nuts and/or washers can be used to space the LCD board out from the panel (see the photo on page 86).

Finally, drill the holes for the rotary encoder, pushbuttons and mounting screws as shown in Fig.21(a). This can be used as a template, but make sure it's far enough away

from the LCD screen mounting location that the two boards will not foul each other.

We attached our control board to the rear of the front panel using 9mm M3 tapped Nylon spacers, with black machine screws holding it on at the front and nickel-plated machine screws at the rear. Ensure that the holes are large enough to prevent the switches from binding.

You can then attach the rotary encoder knob and connect the LCD panel and control board back to the CPU board and power supply board respectively, as per your earlier tests.

Performance

Fig.20 shows the output of a spectrum analyser connected to one pair of outputs on the DSP Active Crossover. A pure 1kHz sinewave is being fed into the inputs. This shows up in the spectral analysis as a large spike just to the left of centre.

The readout below shows that this fundamental signal measures -9.72dBFS for the left channel and 1.62dBFS for the right channel. "dBFS" stands for 'decibels full scale'. In this case, the full-scale output is around 2.2V RMS, so those signals are at around 0.72V RMS and 1.8V RMS, respectively.

The smaller spikes you can see to the right of the fundamentals, at 2kHz, 3kHz etc are the harmonics, ie, the distortion products resulting from the signal passing through the unit. The most significant are at 3kHz and 5kHz, ie, the third and fifth harmonics.

The software measures the relative levels of each harmonic and the fundamental (first harmonic) and feeds them into a formula to calculate the total harmonic distortion (THD) ratio for each channel, which it's showing as 0.0004% for the left channel (remember, that's the one with the reduced signal level!) and 0.0001% for the right channel.

Note that if you incorporated the noise measurement (seen in the wiggly bases of the plots), these figures wouldn't be quite as good, but they're vanishingly low either way, and you certainly won't complain about the sound quality coming out of this device.

Using it

The DSP Active Crossover is set up and controlled using a menu system. Menu entries are shown on the graphical LCD while the rotary encoder and two pushbuttons are used to scroll through entries, select them and go back to the start. The various menu screens are shown in the panels overleaf and on these pages, along with a description of each one.

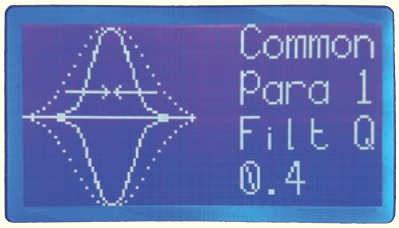
After showing two splash-screens in quick succession, the unit defaults to the volume control screen. This allows you to use it as a preamp, varying the volume with the rotary encoder knob, from -104db up to +12dB (the default is 0dB). Pressing either button (or the knob, if your rotary encoder has an integral button) takes you to the main menu, which has four options.

The rotary encoder selects between those options, while button S2 or the integral rotary encoder pushbutton selects the current option. This button is used as an "Enter" key while button S1, at right, acts as "Escape", to go back to the main screen without making any further changes.

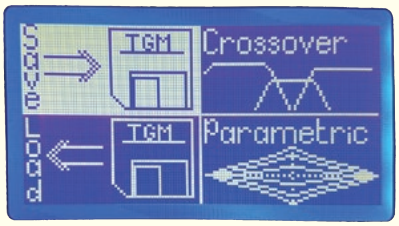
Once you've selected one of the options, you use S2 to cycle through the available sub-options and the rotary encoder to make changes to those options. SC

... Screen25: the centre frequency adjustment screen. Select a frequency from 15Hz to 15kHz using the rotary encoder, then press S2 to...

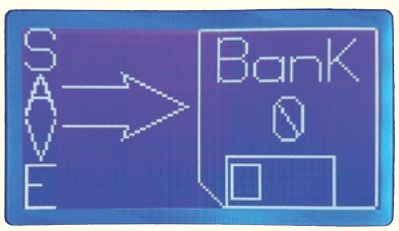
Screen26: adjust the gain or cut for this equaliser band, from -10dB to +10dB. Pressing S2 again...



Screen27: lets you set the Q of the filter, to a value between 0.1 and 10, which affects how wide a range of frequencies it affects.

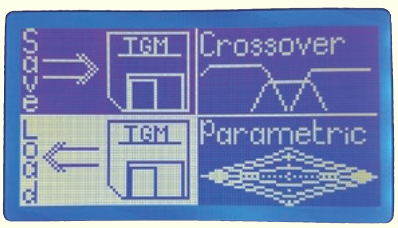


Screen28: back at the main menu, this time we've selected the Save option. Pressing S2 brings us to...

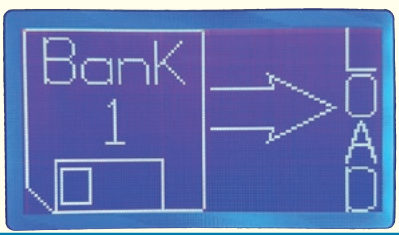


Screen29: a screen where you can choose one of three settings banks to save to. Use the rotary encoder to select one, or press S1 to abort. Press S2 or the knob...

Screen30: to save the settings to EEPROM. This screen is displayed for a short time, then the display returns to the default screen, ie, volume control mode (Screen03).

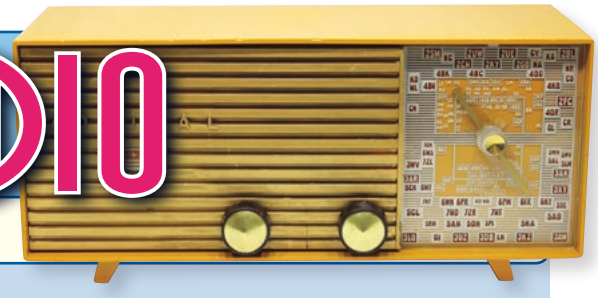


Screen31: the final option in the main menu is to load the settings you have saved. Bank 0 is loaded by default at start-up. To load a different configuration, select this option and press S2...



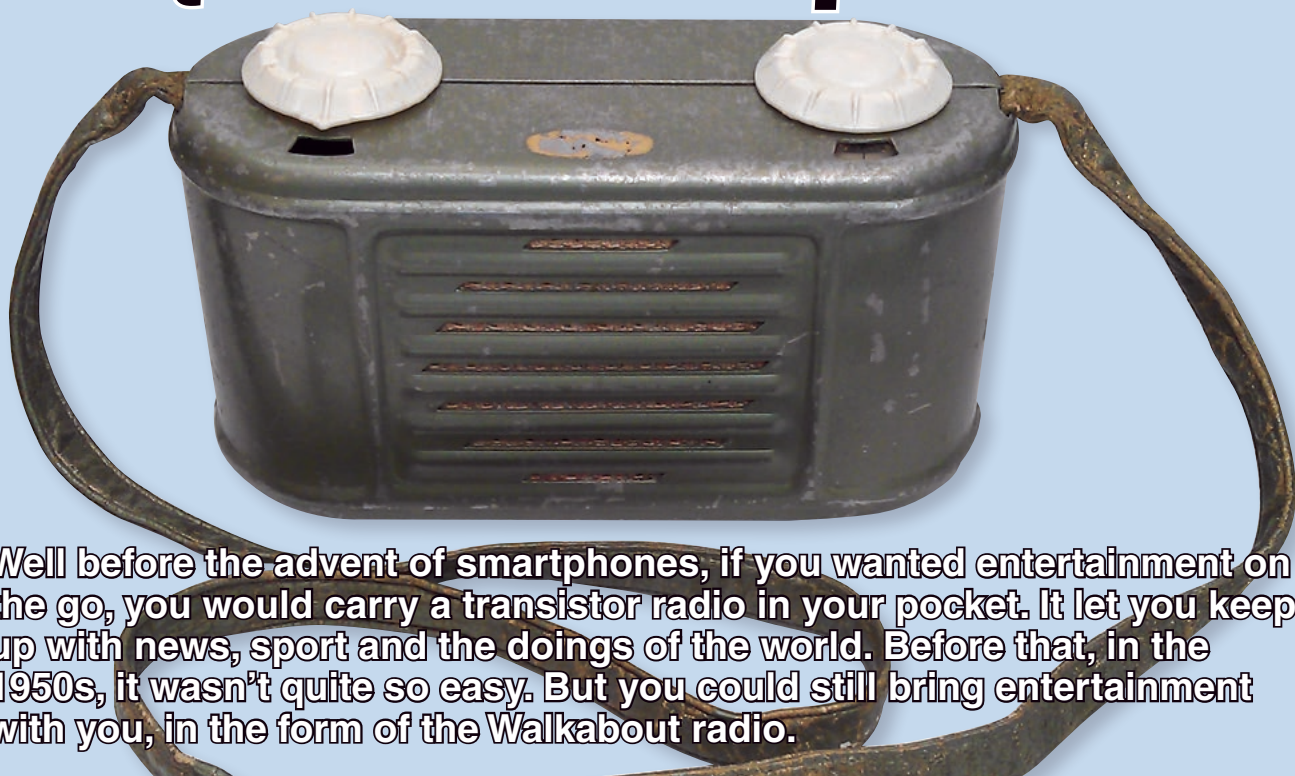
Screen32: then select a bank to load using the rotary encoder, and either press S2 to load it, or S1 to abort and go back to the volume control screen.

VINTAGE RADIO



By Ian Batty

Adelaide-made National AKQ Walkabout portable



Well before the advent of smartphones, if you wanted entertainment on the go, you would carry a transistor radio in your pocket. It let you keep up with news, sport and the doings of the world. Before that, in the 1950s, it wasn't quite so easy. But you could still bring entertainment with you, in the form of the Walkabout radio.

I bought this set at an HRSA auction in 2015, attracted by its unusual appearance. Since an all-metal case would have prevented signal pickup, I wondered how the designers made it work. It took me some time to figure out what it was, as there is no apparent manufacturer's mark. The Ducon capacitors and Philips-branded valves told me that it was made somewhere in Australia.

A fellow HRSA member told me it was made by National, in Adelaide, confirmed by the newspaper advertisement shown later in this article. I went to www.radiomuseum.org and found a National set from 1948 listed, the AKQ, but with no circuit diagrams or photos.

Two similar radios

I emailed Kevin Chant and he helpfully sent me a copy of the circuit diagram and alignment guide, from the 1947 Australian Official Radio Service Manual (AORSM), on page 333.

The AKQ is based on the Astor KQ, except that the KQ is in a more conventional "lunchbox" case with a standard loop antenna in the flip-up lid. There are a few other component variations between the two.

It's a four-valve set with the usual lineup of a 1R5 converter, 1T4 IF amplifier, 1S5 demodulator/audio preamplifier and 3S4 audio output stage. But it's just unusual enough to be interesting. And it works pretty well, too.

National's circuit shows the converter's anode connecting to HT through the IF primary, then via item 24 (a 10kΩ resistor) to the screen and HT. This is wrong; the circuit diagram presented here has been corrected. Astor's KQ circuit is correct and easier to read. National's drawing office followed Astor's simple component numbering principle (#1, #2, etc).

Both the National and Astor circuits show voltage readings for a 1kΩ/V meter, but the readings shown for the 1S5 screen and 3S4 grid are misleading – a 1kΩ/V meter would have given much lower readings at these points and would not give a useful measure of circuit function.

The AKQ Walkabout and the Astor KQ share a rather odd supply switching arrangement: the LT positive end is

switched, but the HT supply's negative end is switched. Most component values are identical between the two sets.

The principal differences are the cabinets and the KQ's use of a conventional, multi-turn frame antenna. The KQ service notes are comprehensive, and the circuit diagram is much better laid out and more legible.

Construction and restoration

It's a conventionally constructed valve set, using valve sockets and tag strips mounted onto a pressed-and-punched steel chassis. It uses point-to-point wiring of rubber-covered single-strand tinned copper.

With age, some of the insulation had degraded and frayed off. Rather than pull it entirely to pieces, I replaced the worst of the wiring. The soldering quality was mediocre; the wires were not wrapped around the tags before soldering, although this did make component replacement easier.

The wiring around the audio stage was pretty cramped, making it hard to get test prods onto socket pins. Given the set's compact construction, though, such cramping is to be expected.

Valve removal and insertion can be a bit tricky. I found removal easiest by placing a thin screwdriver blade between the valve base and chassis, then easing the valve out. Replacement was sometimes accompanied by the utterance of magic spells known only to technicians and best not repeated here.

Circuit description

The circuit begins with #35 (aerial strap assembly), not shown on the AKQ circuit. It's a simple length of braided copper, stitched inside the leather carry strap.

The aerial strap feeds into the matched primary of antenna transformer #29. Given the small size of the almost-one-turn antenna strap, we need a bit of magic to boost the signal.

Transformer #29 does this admirably, using a combination of step-up ratio and tuned-circuit multiplication. It yields a gain of some 43 times. As the adage goes, the best RF stage is a good antenna circuit.

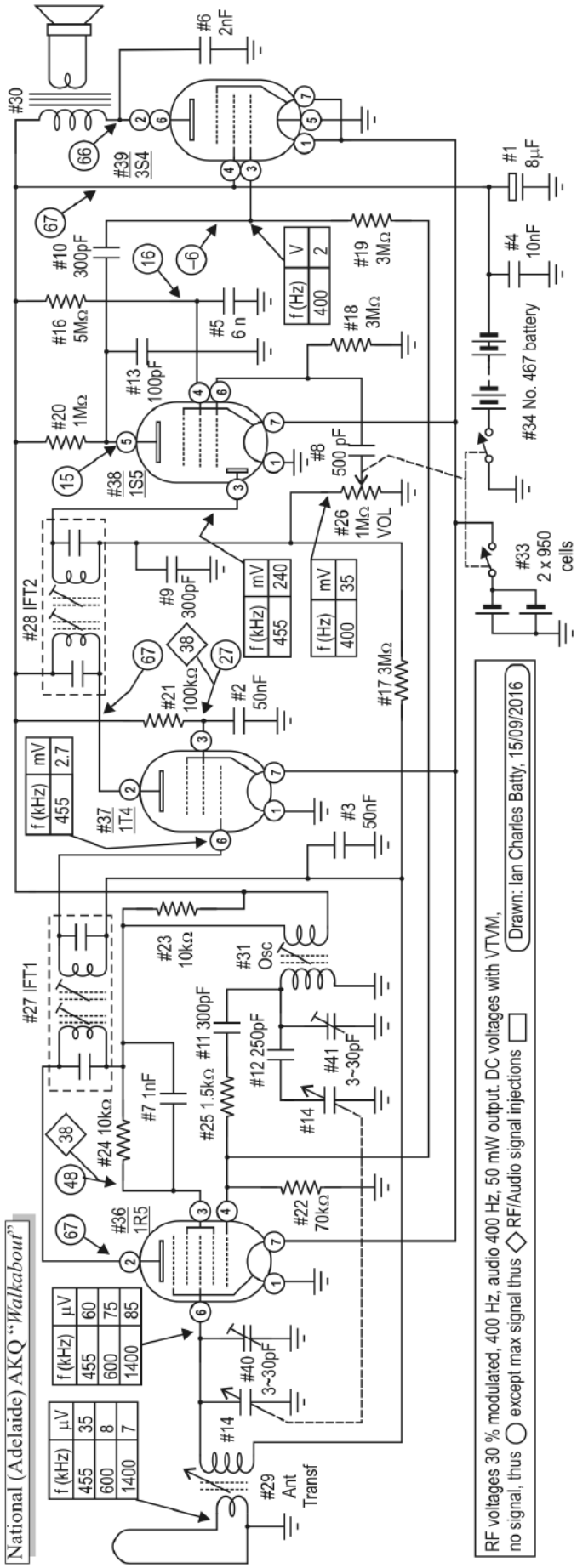
#29's high-impedance secondary feeds the aerial tuning gang and the converter's signal grid, grid 3 (pin 6). Converter #36 (a 1R5) is a pentagrid, modelled on the 6SA7/6BE6.

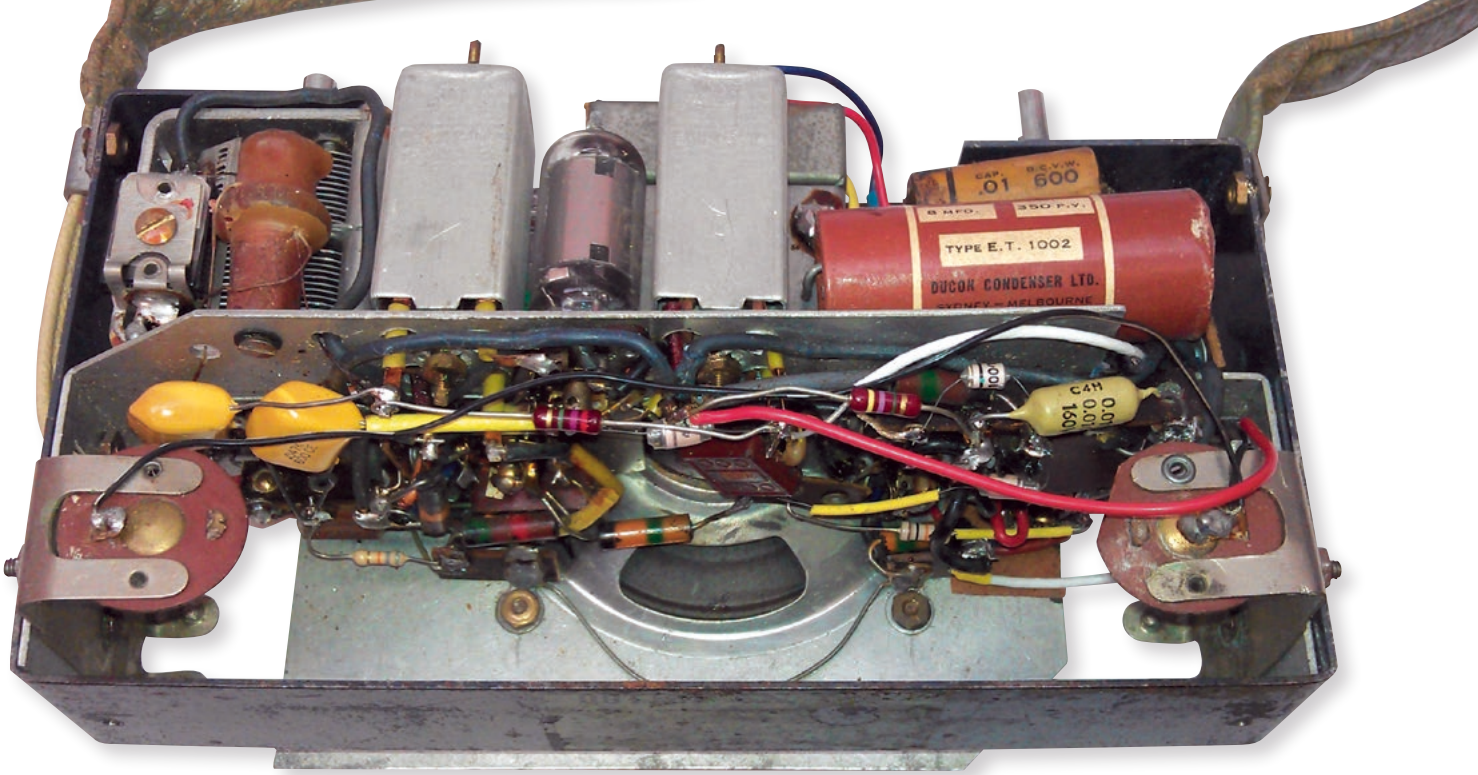
Grid 3 is used as the control grid while grid 5 (pin 2) acts as the oscillator anode. Grids 2 and 4 (pin 3) are tied together, isolating signal grid 3 from the oscillator section and ensuring that changes in grid 3's bias (due to AGC action) do not pull the oscillator off-frequency. So grids 2 and 4 act as screen grids.

Ideally, a screen grid is at RF/signal ground, so the preferred 6SA7/6BE6 converter design used a cathode-grid Hartley feedback circuit with a tapped oscillator coil. This allowed the combined screens (grids 2 and 4) to be bypassed to RF ground as you'd expect.

Since the 1R5 has no separate cathode, cathode feeding is complicated to implement. You'll usually see the screen grids (grids 2 and 4) carrying the oscillator signal and used as the oscillator anode, or (as in the Walkabout), the two screens and the anode "collected" at local oscillator (LO) frequencies to form the oscillator circuit's anode, drawing HT current through the oscillator coil primary.

Valve local oscillators work in Class C, where the grid is driven into conduction during the positive peak of the





The case and chassis of the National Walkabout AKQ are made from metal, with the aerial stitched into the leather carry strap. The components are connected via point-to-point wiring, making for a packed chassis when the batteries are included.

operating cycle, with anode current cut off at the opposite peak.

A novel output stage bias generation method

Driving the grid positive forces it into rectification, establishing an overall negative bias on the grid. It's usually a few volts negative, enough to pick off as bias for output valve #39 (a 3S4), via a 3MΩ resistor (#19). Bias for the output stage relies on a fairly constant LO grid current to generate a constant grid bias, and low (or no) LO activity will reduce or eliminate output stage bias.

On test, the bias voltage varied around -5V to -6V as the set was tuned from its low end to the high end. This bias is developed across the 70kΩ LO grid resistor (#22), with 1.5kΩ grid stopper (#25) aided by a 10kΩ resistor (#23) to give more constant LO activity and (hence) output bias.

The converter's anode drives first IF transformer #27, with conventional slug-tuned primary and secondary. The secondary feeds IF amplifier #37, a 1T4. This stage has an unusually high screen dropper (100kΩ; #21). 50nF capacitor #2 provides bypassing at intermediate frequencies (IF).

Starved screen IF stage

The 1T4 data sheet shows a screen voltage of 67.5V for an anode voltage of 67.5V, so this is a "starved screen" design. It's similar to the previously-described Astor Aladdin FG radio (August 2016; siliconchip.com.au/Article/10049). The FG, like many sets with two IF stages, uses the starved design to reduce gain and prevent IF feedback.

Astor's notes for the KQ describe it as a means of "reducing IF current drain". This reduces the potential total HT current by some 30%, but only reduces the potential gain by some 20%. So the reduced power consumption does appear justified.

The IF amplifier feeds the second IF transformer #28, also double-slug-tuned. Its secondary feeds the diode of diode/pentode #38 (pin 3), a 1S5. The rectified audio signal appears across 1MΩ volume control potentiometer #26 from the first grid of the 1S5 (pin 6), which also contains switching for the 1.5V LT and 67.5V HT supplies. 300pF filter capacitor #9 removes IF pulsations from the rectified output.

The AGC voltage is fed, via 3MΩ resistor #17, to the IF and converter control grids, and filtered to remove AC audio signals by 50nF capacitor #3. The pentode section of the 1S5 amplifies the demodulated audio and it is then fed to the output stage grid.

Audio preamplification stage

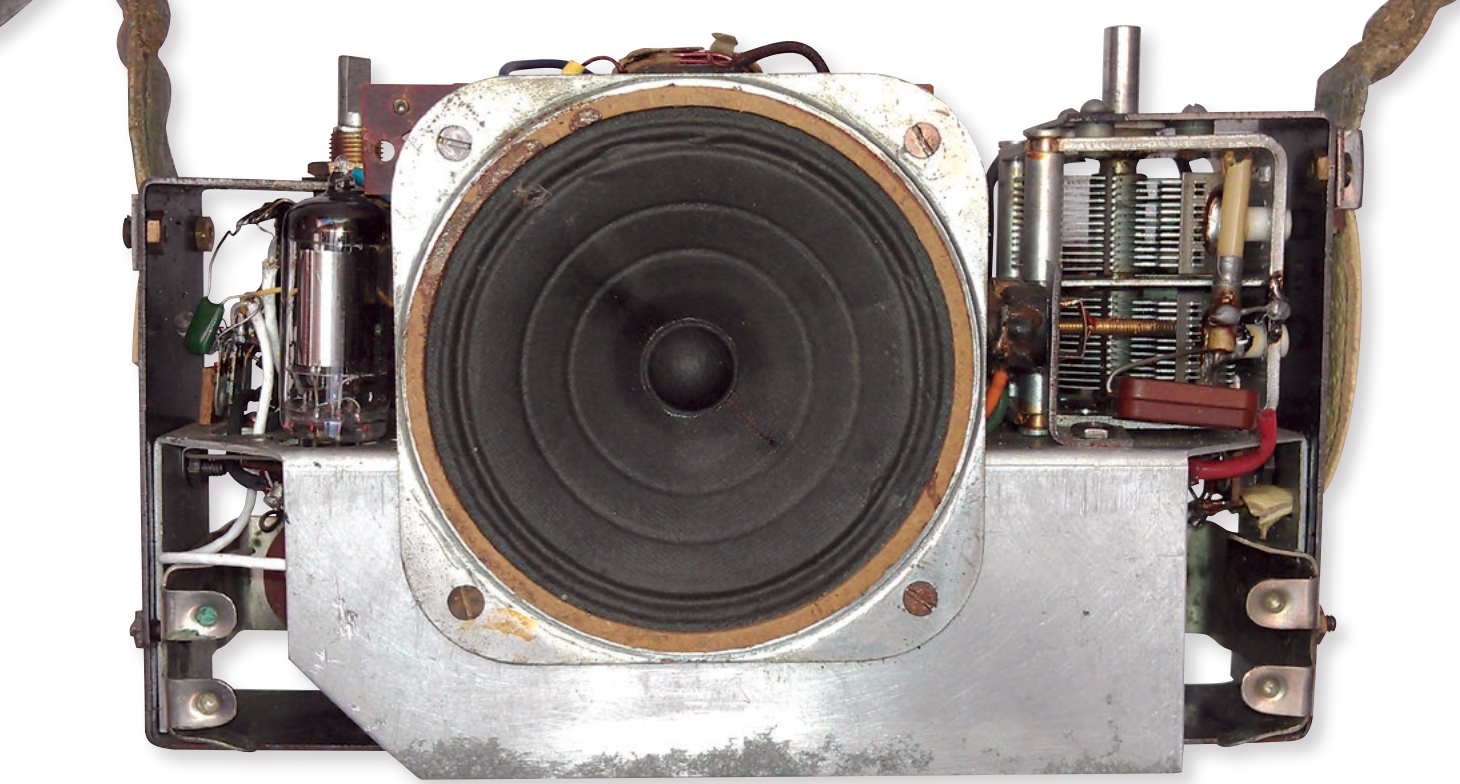
In common with first audio stages in battery radios, the audio amplification stage built around the 1S5's pentode uses "contact potential" bias. The relatively low value of grid resistor #18 (only 3MΩ rather than the more usual 10MΩ) allows the grid to drift negative due to the electron "cloud" surrounding the filament. This effect, though weak, is enough to provide a suitable bias for the 1R5.

The anode load resistor (#20) and screen dropping resistor (#16) values are quite high; 1MΩ and 5MΩ respectively. This combination, although only allowing an anode current just under 100µA, provides a stage gain around 50 times. The high value of #16 allows a low value for screen bypass capacitor #5 (6nF) compared to hifi designs using the indirectly-heated 6AU6.

Audio output stage

The 1S5's signal couples to output valve 3S4's grid. It's has a centre-tapped filament which allows it to operate from 3V or 1.5V (with the two halves in parallel). You'll see the 3V configuration used in series-filament designs.

The 3S4 needs a bias of around -7V, and the most obvious source is a back-bias resistor between the HT battery's negative connection and ground. It's a simple method, but it steals that voltage from the battery supply.



The case was made from Duralumin, and the chassis was likely made of a similar material. The speaker (likely a 4Ω Rola or equivalent) attaches to the chassis and to the other side of a board which also seats the output transformer.

Two alternatives exist: a separate bias battery (used mostly in military equipment with multi-voltage battery packs), or a tap from the local oscillator's grid bias resistor. As described above, tapping the LO's grid bias is a neat engineering solution.

The 3S4 feeds output transformer #30. The Astor KQ circuit has the core connected to the HT supply. Since this puts the fine wire of the primary at HT potential, any possible electrolytic corrosion of the primary is prevented. This technique is normally used only with "potted" transformers, for safety.

Finally, 2nF capacitor #6 is there to damp the output transformer's natural resonance. It's better connected directly across the primary rather than having one end to ground. If the capacitor goes short circuit, this may draw enough current to burn out the transformer primary.

Cleaning it up

The set was in good cosmetic condition, apart from wear on the leather strap. Electrically, it offered several challenges.

Turning up the volume, I was met by an ear-splitting shriek from about 20% to 75% of the volume pot's travel. Contact cleaner had a minor effect, so it had to be oscillation. I thought it might be due to capacitor #6 being faulty, as this is responsible for damping the output transformer's natural resonance. But putting another 2nF in parallel forced the set into even more violent oscillation.

It was odd that it only happened with the volume control over part of its travel. Holding a screwdriver blade onto the volume pot's wiper, and touching the insulated lead from the 3S4 output's anode lead with a finger, made it worse.

So I reckoned it was due to audio feedback. I tried putting in a new HT bypass capacitor but that made no improvement. I then shielded the audio leads from demodulator to volume control pot, thence to the 1S5 grid, also resulting in no improvement. I then connected one side of the speaker's "floating" voice coil to ground, with no improvement.

Having already replaced 100pF capacitor #13, I bit the bullet and added a 470pF capacitor from the 1S5 grid to ground. Since this would be in series with 300pF capacitor #10, it would potentially reduce coupling from the volume pot, so I increased capacitor #10's value to 4.7nF.

That solved the problem. Whatever bizarre feedback path that had existed was eliminated. I think that this only happened near half volume because feedback onto the 1S5 grid is zero at zero volume, as the pot shunts the grid to AC ground. At full volume, there won't be as much shunting, but the demodulator circuit would load the 1S5 grid, reducing potential feedback.

At half volume there's minimal damping, allowing the circuit to take off. It's similar to another radio I was working on in the past, which would hum at around half volume; the dressing of the volume pot leads past the rectifier section had allowed hum pickup, and was loudest at half volume when the first audio grid had minimum loading.

With a worst-case impedance from the 1S5's grid to ground of some 300kΩ+ at 1kHz, it wouldn't need much stray capacitance feeding back from V4's anode to V3's grid for the circuit to take off.

Did Astor's KQ suffer a similar problem? Maybe. The KQ added a 50pF capacitor from the volume pot's wiper to ground. It's hard to see what useful effect such a small additional component could have in an audio circuit. But it might be just enough to prevent oscillation.

And maybe that's where the designers of the National AKQ got caught out. Astor's 50pF capacitor was definitely not installed in National's AKQ.

Maybe National were lucky with most sets, and mine is one of a few that suffered from oscillation. Having fixed it, I re-checked the 1S5's voltages. Finding the screen a bit low, I replaced

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There's no need to stop and listen to that radio programme you MUST hear. With a NATIONAL Walkabout you can listen as you move about, wherever you go. Built for your personal use, the NATIONAL Walkabout can be carried like a shoulder bag. It weighs only 4½ lb. . . . it measures only 8½ x 4½ x 3½ inches. Its carrying strap is the aerial, and FOUR midget valves give radio reception equal to the largest 4-valve portable. Get your NATIONAL Walkabout TODAY.
Features of this Amazing Set:—
LIGHT "DURALIUM" CASE finished with brocade enamel looks well, wears well. MINIATURE COMPONENT PARTS and "ANISOTROPIC ALNICO" MAGNETIC 3 in. ROLA SPEAKER give as much reception power as larger portables. TWO TORCH CELLS and ONE 67½ V. "MINIMAX" Battery supply sufficient power to operate the set perfectly.
"The National
WALKABOUT"
4-VALVE PERSONAL-PORTABLE RADIO
Another National
ACHIEVEMENT IN RADIO

bypass capacitor #13 and series resistor #16 with new components.

IF alignment

I was able to align the first IF stage transformer primary and secondary without a hitch. But upon attempting to align the second IF stage primary, I ran into a problem.

Driving the slug all the way in failed to produce a peak, while the secondary tuned up just fine.

Winding continuity was OK, so I removed the IF transformer and slipped its can off. A simple resonance test showed that the winding was not tuning up. Replacing the 50pF tuning capacitor remedied the problem and the IF stage tuned just fine.

The set now appeared to be going OK, but why wasn't the AGC working? I didn't need my output meter to tell me the volume was all over the place between local and remote stations.

The 1T4 IF amplifier has a screen resistor, so this is a good place to look for a voltage rise as the AGC takes over and reduces the valve's current. Measuring the voltage across this showed almost no variation with signal strength.

This was similar to the previously-described Aladdin FG set. The culprit in the AKQ was AGC filter capacitor #3, a 50nF paper capacitor which was leaky. Since the AGC signal is supplied via 3MΩ resistor #17, it doesn't need much leakage to shunt the AGC signal to ground. A new polyester cap fixed it. I also replaced IF screen bypass capacitor #2 and some other caps and resistors that looked suspect.

How good is it?

RF performance, taking into account the single-turn antenna, is good. For a 50mW output, it needs around 350µV/m at 600kHz and 400µV/m at 1400kHz for signal-to-noise ratios of 20dB and 25dB respectively.

Input levels at the converter grid, as shown on the diagram, seemed a bit high. This set uses simple (undelayed) AGC where gain reduction applies even on weaker signals. Shorting out the AGC line gave about double the sensitivity for a 50mW output. So it's true that simple AGC does compromise a set's ultimate sensitivity.

Be aware that I used my ferrite rod radiator for these results, and that it was only specified for radiation into another ferrite antenna. If an antenna guru is reading this, maybe they can comment on the validity of my test setup. The results appear to tally with other sets using multi-turn loop antennas, so I'm confident in listing them.

RF bandwidth is around ±1.7kHz at -3dB; at -60dB, it's ±29kHz. AGC action is only fair; a 6dB increase in input signal strength was almost matched by the same rise in the output signal. With a 40dB input rise, though, the output rise was around 20dB.

Audio response is 240~2800Hz from volume control to speaker; from the antenna to the speaker it's 270~2300Hz.

Audio output is only about 120mW at clipping, with 10% THD. At 50mW, THD is around 7.5%; at 10mW, it's about 4.5%. The output is low compared to manufacturer's figures which have the 3S4 giving 180mW with a 67.5V HT. Everything tested out OK, however, and the set is loud enough for its intended use.

The set's performance does depend on the orientation of the antenna strap – my bench measurements required careful orientation to get the sensitivities quoted.

In practice, it's best used with the strap opened out and pointed in line with the direction of the desired station. Loops work best with a difference in magnetic induction from one side to the other, ie, with the loop's plane pointing to the transmitter.

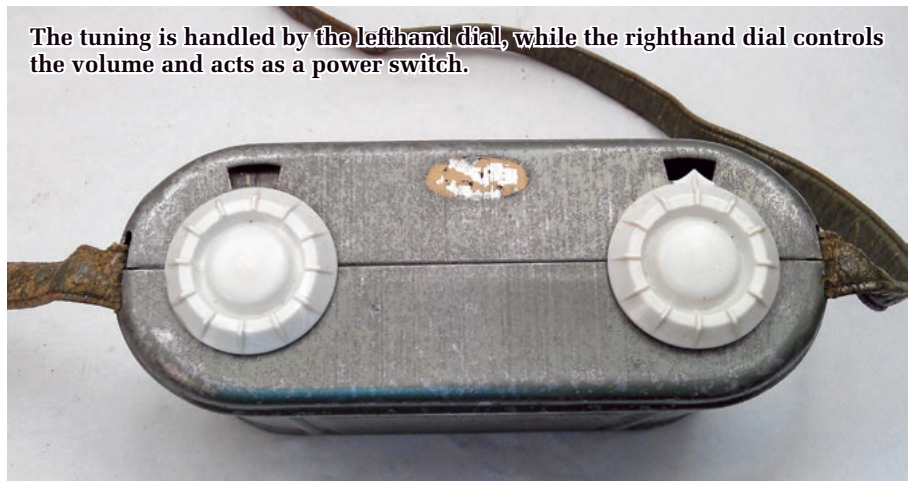
You can just put the strap over your shoulder and face towards (or away from) the station.

The set picked up 3WV Western Victoria at a reasonable volume, a station some distance from me.

I'm happy with the Walkabout as a "town portable". It's an example of Aussie ingenuity that helped make radio programs available to anyone, anywhere, any time.

If you want more information but don't have access to the AORSM, check out the HRSA's Yellow Pages at hrsa.asn.au At least one member offers the complete collection on CD, and it's a most valuable resource if you're into old Australian radios.

Thanks to Kevin Chant, Stuart Irwin and Mike Osborne for helping me track down the circuit diagram. SC



The tuning is handled by the lefthand dial, while the righthand dial controls the volume and acts as a power switch.

CIRCUIT NOTEBOOK

Interesting circuit ideas which we have checked but not built and tested. Contributions will be paid for at standard rates. All submissions should include full name, address & phone number.

Guitar practice preamplifier based on inverters

This guitar preamplifier uses six unbuffered inverters in a single package (74HCU04) to provide amplification, and runs off a USB 5V power supply.

This IC can be used either as low-delay digital inverters or high-gain inverting amplifiers (as in the TOSLINK to S/PDIF Converter, October 2010, siliconchip.com.au/Article/319 & High-Sensitivity Magnetometer, December 2018, siliconchip.com.au/Article/11331, although the latter used a similar 4069UB IC).

"Unbuffered" refers to the fact that each inverter consists of just a single stage, ie, two small Mosfets in a totem-pole configuration with their gates and drains tied together, acting as a non-linear high-gain inverting amplifier.

A guitar practice amplifier does not need to be highly linear nor particularly loud. CMOS logic chips have a high input impedance well-suited for connecting to an electric guitar pickup. So that IC is suitable for this application, if a bit unusual.

Most guitars have volume control pots, as do some headphones used by musicians, so this circuit has a fixed gain. The guitar is connected via jack socket CON3. A 10MΩ resistor provides ground biasing while keeping the input impedance high, and the 100pF capacitor filters out any RF picked up by the guitar or lead.

The signal is then AC-coupled to the first gain stage via a 100nF series capacitor. This gain stage is built around inverter stage IC1f and has a fixed gain of around two times, set by the ratio of the 1MΩ and 470kΩ resistors. This works similarly to an op amp based inverting amplifier but is less linear, as the open-loop gain is a lot lower.

This stage is self-biasing because the two internal Mosfets conduct a similar amount of current when the input and output pins are near mid-supply. So the DC level at the input tends to settle at around 2.5V.

The output of this stage is then fed to a second gain stage comprising the remaining five inverters (IC1a-IC1e) connected in parallel. This stage has a gain of around five times, set by the ratio of the 100kΩ and 20kΩ resistors.

A 10Ω resistor in series with the output of each inverter ensures that they share the load current more-or-less evenly. The five inverters are paralleled so that they can drive 32Ω headphones to a reasonable volume.

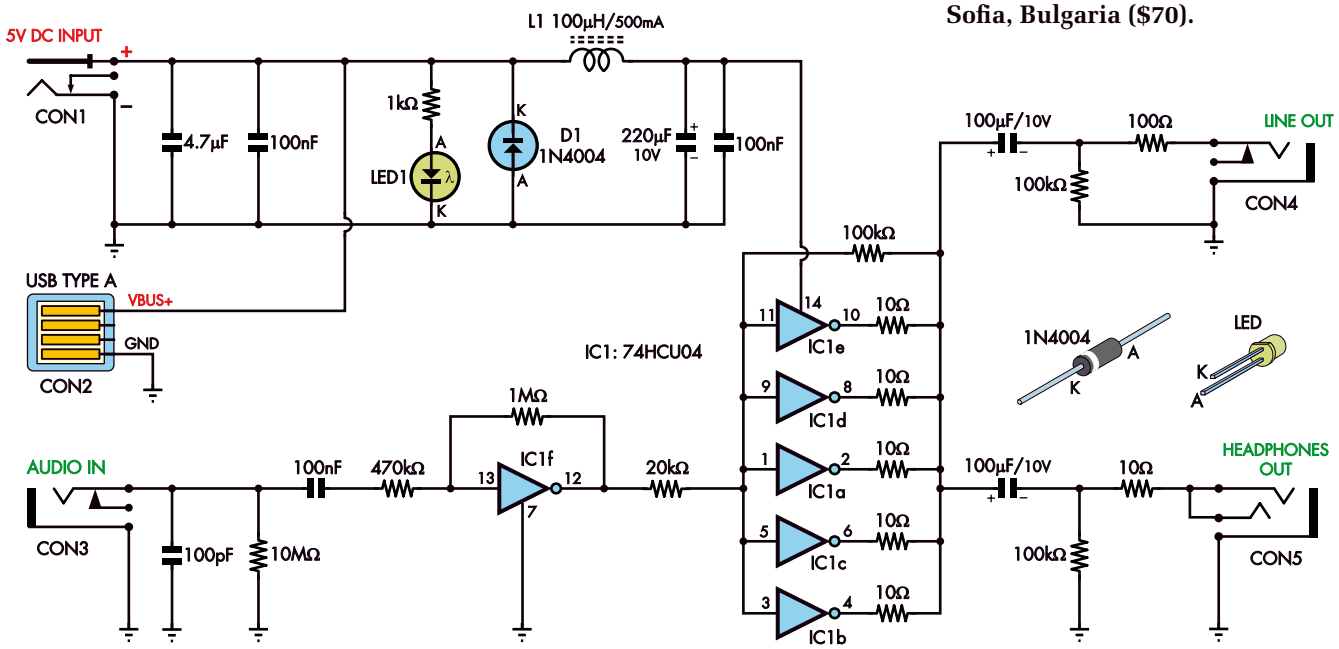
The headphones at CON5 are fed via a 100µF capacitor, to remove the 2.5V DC bias from the amplified signal, with a 10Ω series resistor to slightly increase the impedance seen by the amplifier and to improve stability.

The signal is also sent to output CON4 via another 100µF capacitor and a 100Ω series resistor. This can be used to connect an amplifier to drive a small speaker.

The circuit is powered with 5V applied to either DC barrel socket CON1 or USB socket CON2. The supply is decoupled by two small capacitors (the USB specification limits the capacitance directly across a socket) with LED1 indicating power is applied and diode D1 protecting the circuit against reverse supply polarity.

100µH inductor L1 forms a low-pass filter in combination with the following 220µF capacitor, reducing supply noise which may otherwise be fed through to the sensitive amplification stages.

Petre Petrov,
Sofia, Bulgaria ($70).



74LS- and 74HC-series logic IC tester

This circuit checks digital logic ICs which are plugged into an IC socket and displays the results on an LCD screen. It performs a thorough check, applying all possible input combinations and checking that the output pin states are correct. It also automatically switches off power to the device if it draws too much current. It's controlled via a 12-key numeric keypad.

It has support for 70 different types of logic ICs from 74LS00 up to 74LS374. Many of the 74C, 74HC, 4000B series and so on have the same function and pinouts, and as long as they will run with a 5V supply (most will), this circuit can check them, too.

It's based on a DS89C430 microcontroller from Dallas Semiconductor. It is pin compatible with the venerable 8052 and also uses the same instruction set but it has a much larger 16KB of program memory than older 8052-compatible chips.

The 89C430 has a high-speed architecture. It runs at one clock per machine cycle, with a maximum clock rate of 33MHz.

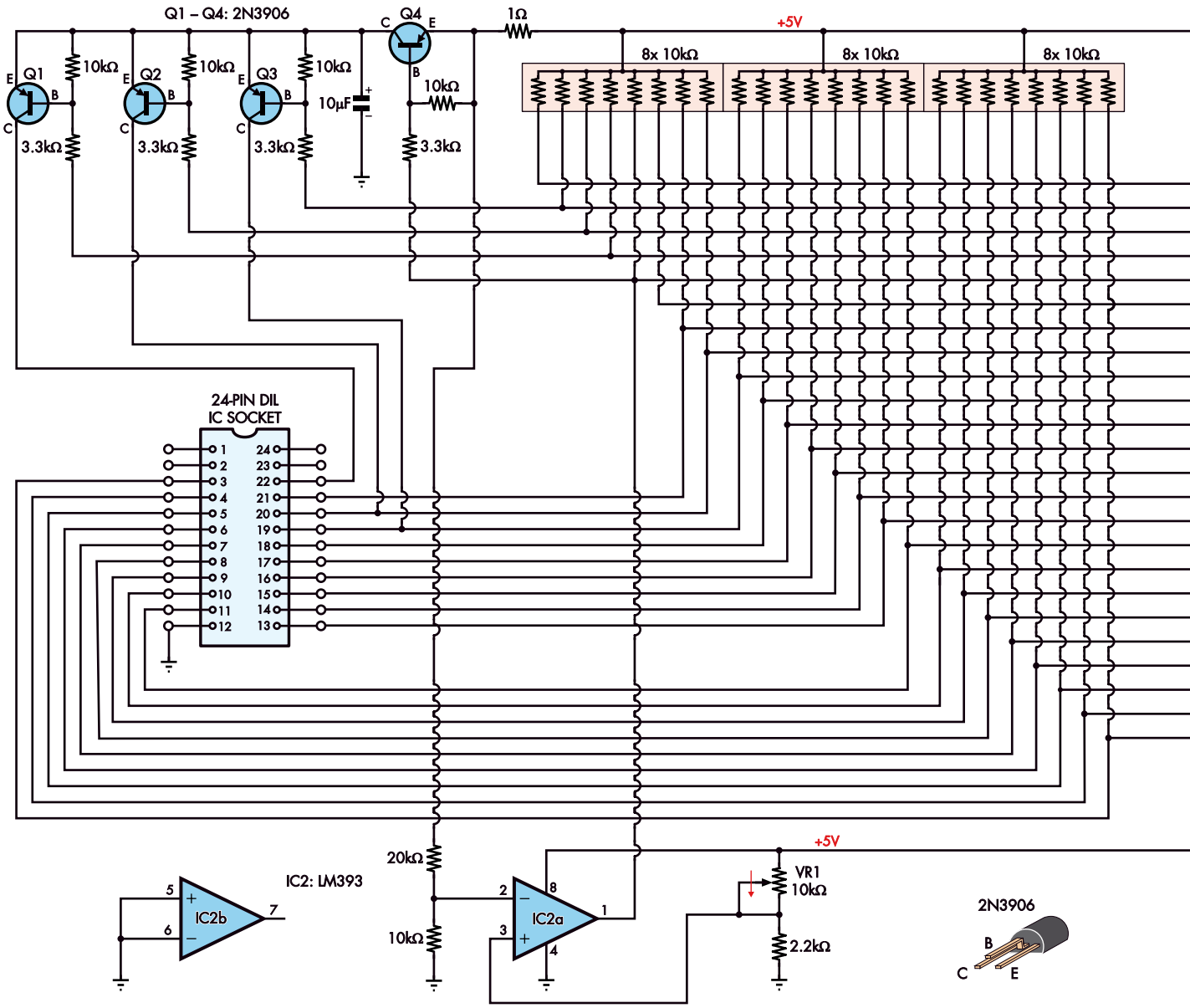
The DS89C430 provides three 16-bit timer/counter, two full-duplex serial ports, 256 bytes of direct RAM plus 1KB of extra MOVX RAM.

The lower-left pin of the socket is permanently connected to GND (0V) as all the ICs in the supported list (and most digital logic ICs) have their ground pin at lower-right and power pin at upper-right.

Since the IC pin count can vary, three different socket pins can be connected to V_{CC} via one of PNP transistors Q1-Q3, under the control of micro IC1. This allows for 14-pin, 16-pin and 20-pin ICs to be powered up and tested.

PNP transistor Q4 is used to switch overall V_{CC} power to the DUT (device under test). That power flows through a 1Ω resistor. The voltage across it is monitored by op amp IC2a and if the current drawn by the DUT exceeds a threshold set by trimpot VR1, IC2a pulls the base of Q4 high, switching it off and cutting power. This is also fed to pin 24 of IC1, so it knows that a fault was detected.

The other pins of the DUT are routed to digital I/O pins on microcontroller IC1. Each one has a 10kΩ pull-up to V_{CC}. IC1 requires external power-on reset circuitry and this is the purpose



of the capacitor, resistor and diode connected from pin 9 to V_{CC} and GND.

Pins 10-16 of IC1 are shared between the alphanumeric LCD screen, which operates in 4-bit mode, and the 3x4 multiplexed keypad, which has a 7-pin connector. The circuit is powered from a 5V supply provided by 5V low-dropout regulator REG1, itself fed from a rectified and filtered 6V AC supply which can come from a 6V AC plugpack or 12V AC centre-tapped transformer.

Alternatively, it could be powered from a 7.5V DC or 9V DC plugpack.

In operation, you use the numeric keypad to type in the suffix of the 74LS device that you wish to test. If the device selected is not found in the micro's database, it displays a message which reads "Not in Library".

Otherwise, it then sets the I/O pins which are routed to the socket as inputs and outputs as necessary, so that each digital output of the logic IC is connected to a digital input on the micro and vice versa.

All the pins on IC1 which are configured as digital outputs are then brought low and the digital outputs on pins 25-27 are set so that the correct transistor (Q1, Q2 or Q3) is enabled to power the selected IC.

You are then prompted to insert the IC in the socket and press a button when you have done so. It then applies V_{CC}.

The micro then checks that the states of its inputs, as driven by the DUT, are correct for the DUT input states being all zeroes.

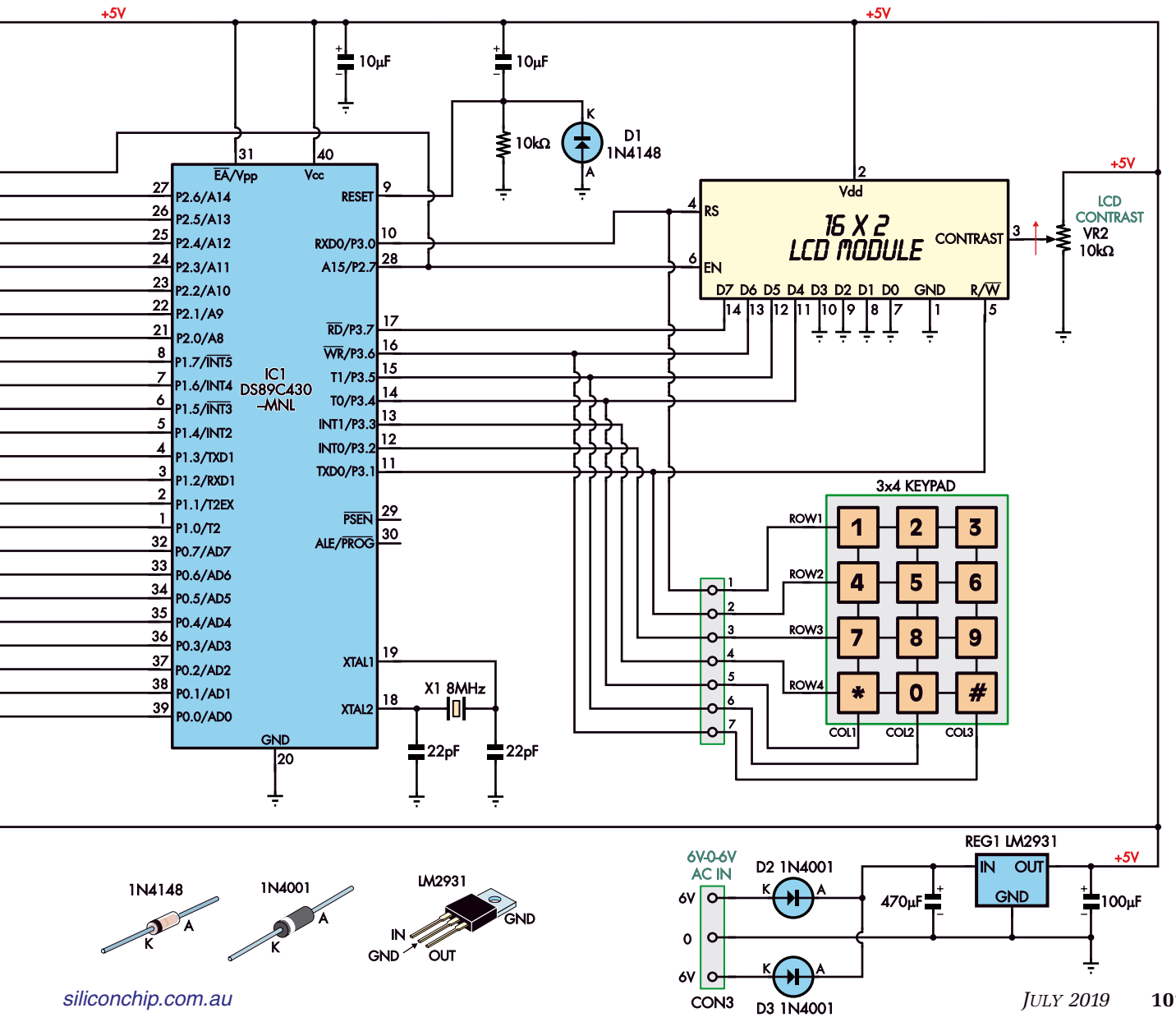
Assuming that's OK, it cycles through all the possible DUT input states and compares the state of its inputs to the truth table for the device being tested. If they all match, the device passes the test. Otherwise, something is wrong and it indicates a test failure.

It at any time an over-current condition is detected, the power to the DUT is cut and an error is displayed on the LCD screen.

You can build the device using point-to-point wiring on protoboard. The firmware and source code (ICtester.bin, ICtester.hex and ICtester.asm) are available for download from the SILICON CHIP website, along with a list of supported logic devices.

IC1 is programmed over a serial port but you will need a suitable programming rig. There's no need to alter its configuration byte from its default value.

Noel Rios,
Manila, Philippines ($75).



Electrocardiogram (ECG) based on a Micromite Explore 100

I wanted to use the ECG project from the October 2015 issue (siliconchip.com.au/Article/9135) without needing to connect it to a PC. So I wrote some software for the Micromite Plus Explore 100 module (September & October 2016; siliconchip.com.au/Series/304) with a 5-inch touchscreen, to provide an ECG display using the October 2015 shield.

Once you've built and tested the Explore 100 and built the ECG shield, combining them is easy. The 5V and GND pins are connected together, providing power to the shield board from the Explore 100, and the digital D7 and analog A0 pins on the shield go to pins 51 and 77 on the Explore 100 respectively.

The only other component you need to add is a 5.6kΩ resistor from A0 to GND. This works in conjunction with the 2.2kΩ resistor in series with the output of the ECG shield, providing a voltage divider to limit the analog output voltage to 3.3V, to suit the Micromite.

The software is called "ECG with Peak detect.bas" and this can be downloaded from the SILICON CHIP website. Load it into the Explore 100 in the usual manner (eg, using XMODEM or MMEdit), then issue the "RUN" command; issuing "OPTION AUTORUN ON" first is a good idea, so it will automatically start at power-up.

You could also use a Micromite Plus Explore 64 with an LCD screen connected. The analog and digital pins used would need to be reconfigured in the software; see the variables "ch1" for the analog input pin and "input_gain" for the gain switch input pin (on lines 28 and 29 of the code).

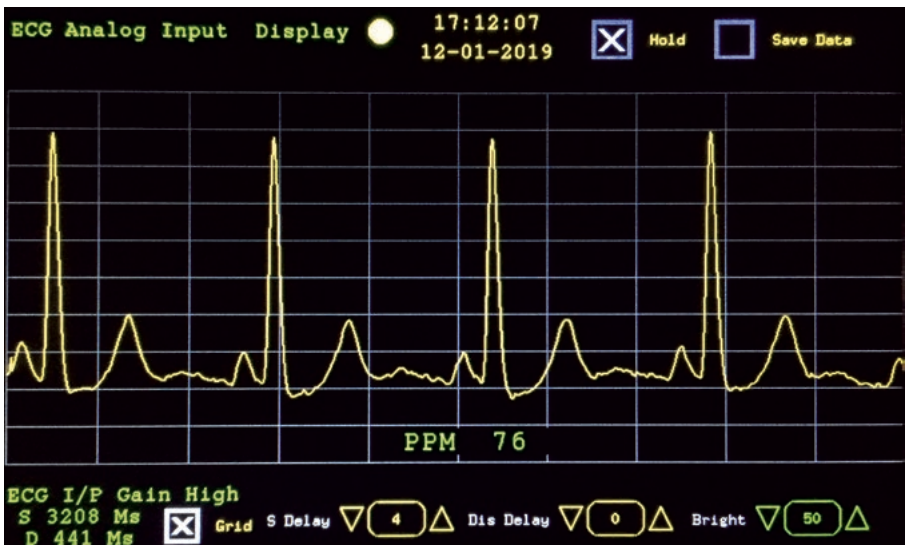
Once sampled, the data is level shifted and scaled relative to the gain setting; a four-period moving average is applied to smooth the data for display.

At the end of data display, the sampled data is checked for the number of peaks above a set trigger value and the number of peaks per minute calculated and displayed.

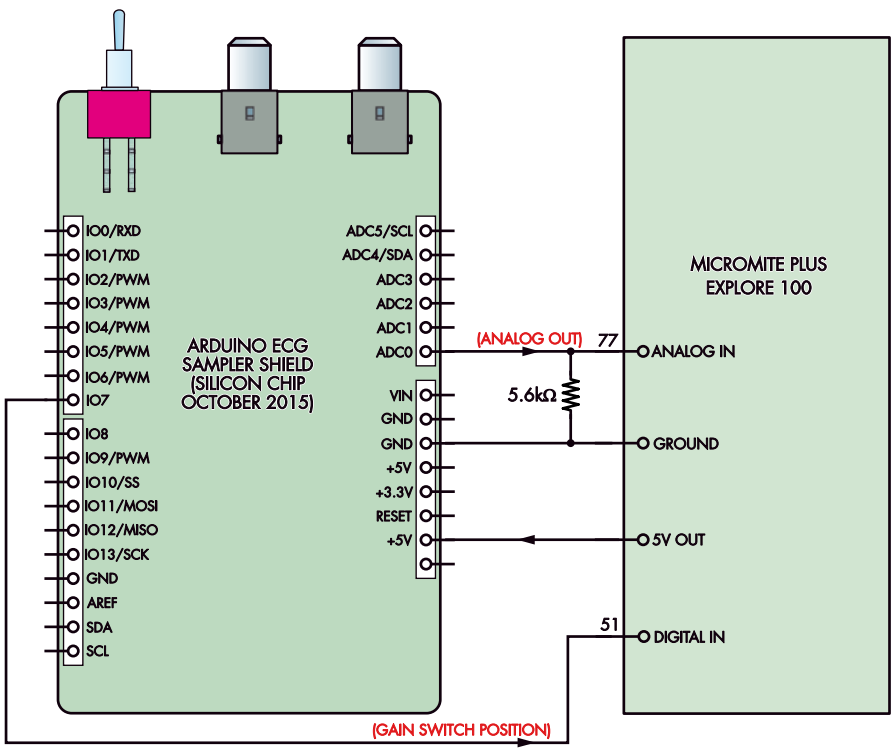
If the save data box is checked, the sampled data is saved in CSV format to SD card with a time and date stamped file name.

The file name contains the date and time that the sample was taken, eg, "ECG 12-01-2019 15-12-38.txt"

Neil Cox,
West Haven, NSW ($85).



▲ **Sample output from the electrocardiogram, displayed on an LCD connected to the Explore 100.**



Features

- Operates in sample-only or sample and display mode
- Selectable sample rate and display update rate
- Time and date display
- Freeze the display (using checkbox)
- Option to save data to an SD card, with time and date stamp in CSV file format
- ECG gain setting display
- Sample and display trace times are shown in milliseconds
- Optional grid
- Display brightness controlled using spinbox
- Peaks are detected and average beats per minute displayed

Horse racing game

The basic idea of this game is to simulate and display a two-horse race. It has three different modes: trot, canter and gallop.

The race is shown on a 4-line, 20-column alphanumerical LCD screen. The image of each horse is formed using eight custom characters, and their legs are animated as they run. See the adjacent screen grab and video.

The circuit is built around an ATmega8A microcontroller and the aforementioned LCD. In all the three modes, the speed of both horses varies automatically and randomly as they run across the display.

This is done using pseudorandom numbers generated by the microcontroller, based on an internal timer value. The random numbers provided by the timer are used to change the speed of each horse.

Thus during the race, the leading horse is sometimes Horse 1 and sometimes Horse 2, and the winner is unpredictable until one horse reaches the finish line (block 20 of the LCD).

To begin the game, switch the unit on. The piezo generates a beep, and two horses appear on the left side of the LCD, and to the right, the message "Press Button" appears on the first two lines, with "Mode: Trot" on lines 3 and 4. A momentary press of mode switch S3 changes the mode.

With the desired mode selected, press play button S2 to allow the two horses to start running towards the opposite end of the LCD.

You will hear a sound similar to hoofbeats coming from the piezo sounder. Once the leading horse reaches the finish line, another sound is made and at the same time, there is a one-second pause to show a snapshot of the winner.

This is followed by a display of the results which includes the name of the winning horse and the distance (number of LCD blocks) covered by each horse (eg, Horse 1: 20; Horse 2: 16). A tie is possible, in which case both horses are listed as winning. After two seconds, the display changes to show the welcome message again and you can play another game.

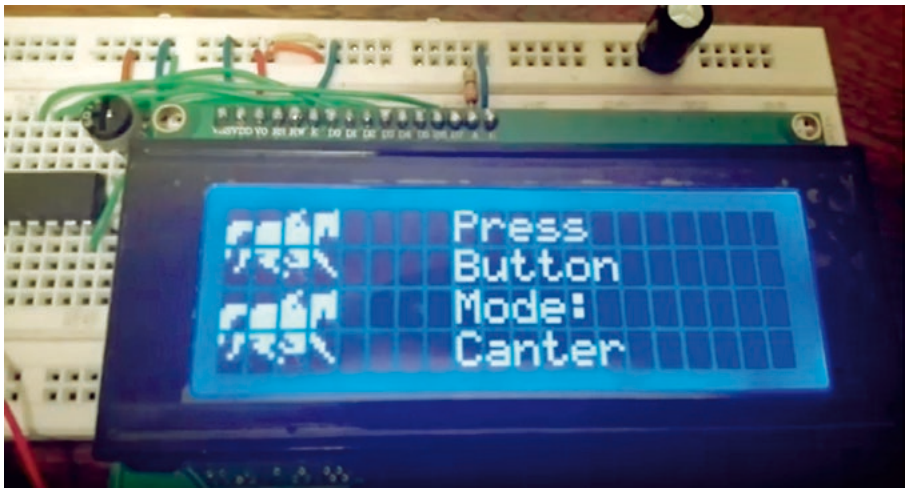
The circuit can be powered by a 5V DC power supply such as a USB charger or plugpack. You can see a video of the prototype in operation at: https://youtu.be/SDTrEUfTreM

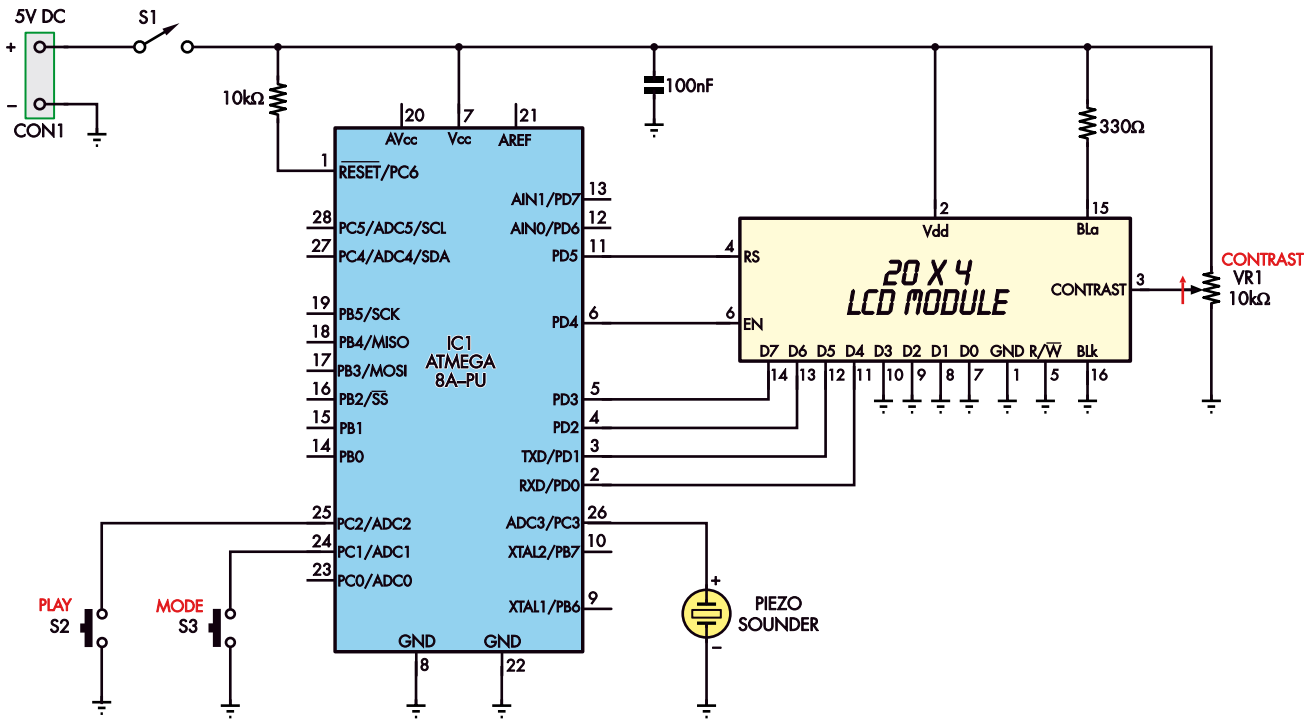
The software was written in BASIC and compiled using BASCOM for AVR microcontrollers. The source code (Triple-mode Horse Race Game.bas) and HEX file can be downloaded from the SILICON CHIP website.

Mahmood Alimohammadi,
Tehran, Iran. ($65)

Editor's note: the circuit for this entry is virtually identical to that of the Dual-mode Digital Dice, by the same author, published in the November 2018 issue. The larger LCD screen and software are the main differences.

Constructors may wish to add a 1N5819 in series with the supply for reverse polarity protection.





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$20 MICROS

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PIC32MX470F512H-120/PT	Micromite PLUS Explore 64 (Aug 16), Micromite Plus LCD BackPack (Nov16)
PIC32MX470F512L-120/PT	Micromite PLUS Explore 100 (Sep-Oct16)
dsPIC33FJ128GP802-I/SP	Digital Audio Signal Generator (Mar-May10), Digital Lighting Cont. (Oct-Dec10) SportSync (May11), Digital Audio Delay (Dec11) Quizzical (Oct11), Ultra-LD Preamp (Nov11), LED Musicolor (Nov12)

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PRINTED CIRCUIT BOARDS

NOTE: The listings below are for the PCB ONLY. If you want a kit, check our store or contact the kit suppliers advertising in this issue. For unusual projects where kits are not available, some have specialised components available – see the list opposite.

NOTE: Not all PCBs are shown here due to space limits but the SILICON CHIP Online Shop has boards going back to 2001 and beyond. For a complete list of available PCBs etc, go to *siliconchip.com.au/shop/8* Prices are PCBs only, NOT COMPLETE KITS!

PRINTED CIRCUIT BOARD TO SUIT PROJECT:	PUBLISHED:	PCB CODE:	Price:
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CURRAWONG CLEAR ACRYLIC COVER	JAN 2015	SC2892	$25.00
APPLIANCE INSULATION TESTER	APR 2015	04103151	$10.00
APPLIANCE INSULATION TESTER FRONT PANEL	APR 2015	04103152	$10.00
LOW-FREQUENCY DISTORTION ANALYSER	APR 2015	04104151	$5.00
APPLIANCE EARTH LEAKAGE TESTER PCBs (2)	MAY 2015	04203151/2	$15.00
APPLIANCE EARTH LEAKAGE TESTER LID/PANEL	MAY 2015	04203153	$15.00
BALANCED INPUT ATTENUATOR MAIN PCB	MAY 2015	04105151	$15.00
BALANCED INPUT ATTENUATOR FRONT & REAR PANELS	MAY 2015	04105152/3	$20.00
4-OUTPUT UNIVERSAL ADJUSTABLE REGULATOR	MAY 2015	18105151	$5.00
SIGNAL INJECTOR & TRACER	JUNE 2015	04106151	$7.50
PASSIVE RF PROBE	JUNE 2015	04106152	$2.50
SIGNAL INJECTOR & TRACER SHIELD	JUNE 2015	04106153	$5.00
BAD VIBES INFRASOUND SNOOPER	JUNE 2015	04104151	$5.00
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DRIVEWAY MONITOR RECEIVER PCB	JULY 2015	15105152	$5.00
MINI USB SWITCHMODE REGULATOR	JULY 2015	18107151	$2.50
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MINI USB SWITCHMODE REGULATOR MK2	SEP 2015	18107152	$2.50
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ULTRA LD AMPLIFIER POWER SUPPLY	OCT 2015	01109111	$15.00
ARDUINO USB ELECTROCARDIOGRAPH	OCT 2015	07108151	$7.50
FINGERPRINT SCANNER – SET OF TWO PCBS	NOV 2015	03109151/2	$15.00
LOUDSPEAKER PROTECTOR	NOV 2015	01110151	$10.00
LED CLOCK	DEC 2015	19110151	$15.00
SPEECH TIMER	DEC 2015	19111151	$15.00
TURNTABLE STROBE	DEC 2015	04101161	$5.00
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VALVE STEREO PREAMPLIFIER – PCB	JAN 2016	01101161	$15.00
VALVE STEREO PREAMPLIFIER – CASE PARTS	JAN 2016	01101162	$20.00
QUICKBRAKE BRAKE LIGHT SPEEDUP	JAN 2016	05102161	$15.00
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MICROMITE LCD BACKPACK, 2.4-INCH VERSION	FEB/MAR 2016	07102121	$7.50
MICROMITE LCD BACKPACK, 2.8-INCH VERSION	FEB/MAR 2016	07102122	$7.50
BATTERY CELL BALANCER	MAR 2016	11111151	$6.00
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RASPBERRY PI TEMP SENSOR EXPANSION	MAY 2016	24104161	$5.00
100DB STEREO AUDIO LEVEL/VU METER	JUN 2016	01104161	$15.00
HOTEL SAFE ALARM	JUN 2016	03106161	$5.00
UNIVERSAL TEMPERATURE ALARM	JULY 2016	03105161	$5.00
BROWNOUT PROTECTOR MK2	JULY 2016	10107161	$10.00
8-DIGIT FREQUENCY METER	AUG 2016	04105161	$10.00
APPLIANCE ENERGY METER	AUG 2016	04116061	$15.00
MICROMITE PLUS EXPLORE 64	AUG 2016	07108161	$5.00
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MICROMITE PLUS EXPLORE 100 (4 layer)	SEPT 2016	07109161	$20.00
AUTOMOTIVE FAULT DETECTOR	SEPT 2016	05109161	$10.00
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MICROPOWER LED FLASHER	OCT 2016	16109161	$5.00
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SC200 AMPLIFIER MODULE	JAN 2017	01108161	$10.00
60V 40A DC MOTOR SPEED CON. CONTROL BOARD	JAN 2017	11112161	$10.00
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GPS SYNCHRONISED ANALOG CLOCK	FEB 2017	04202171	$10.00
ULTRA LOW VOLTAGE LED FLASHER	FEB 2017	16110161	$2.50
POOL LAP COUNTER	MAR 2017	19102171	$15.00
STATIONMASTER TRAIN CONTROLLER	MAR 2017	09103171/2	$15.00/set
EFUSE	APR 2017	04102171	$7.50
SPRING REVERB	APR 2017	01104171	$12.50
6GHz+ 1000:1 PRESCALER	MAY 2017	04112162	$7.50
MICROBRIDGE	MAY 2017	24104171	$2.50
MICROMITE LCD BACKPACK V2	MAY 2017	07104171	$7.50
10-OCTAVE STEREO GRAPHIC EQUALISER PCB	JUN 2017	01105171	$12.50
10-OCTAVE STEREO GRAPHIC EQUALISER FRONT PANEL	JUN 2017	01105172	$15.00
10-OCTAVE STEREO GRAPHIC EQUALISER CASE PIECES	JUN 2017	SC4281	$15.00

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DELUXE EFUSE	AUG 2017	18106171	$15.00
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MAINS SUPPLY FOR BATTERY VALVES (INC. PANELS)	AUG 2017	18108171-4	$25.00
3-WAY ADJUSTABLE ACTIVE CROSSOVER	SEPT 2017	01108171	$20.00
3-WAY ADJUSTABLE ACTIVE CROSSOVER PANELS	SEPT 2017	01108172/3	$20.00/pair
3-WAY ADJUSTABLE ACTIVE CROSSOVER CASE PIECES	SEPT 2017	SC4403	$10.00
6GHz+ TOUCHSCREEN FREQUENCY COUNTER	OCT 2017	04110171	$10.00
KELVIN THE CRICKET	OCT 2017	08109171	$10.00
6GHz+ FREQUENCY COUNTER CASE PIECES (SET)	DEC 2017	SC4444	$15.00
SUPER-7 SUPERHET AM RADIO PCB	DEC 2017	06111171	$25.00
SUPER-7 SUPERHET AM RADIO CASE PIECES	DEC 2017	SC4464	$25.00
THEREMIN	JAN 2018	23112171	$12.50
PROPORTIONAL FAN SPEED CONTROLLER	JAN 2018	05111171	$2.50
WATER TANK LEVEL METER (INCLUDING HEADERS)	FEB 2018	21110171	$7.50
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WIDE-RANGE LC METER (INCLUDING HEADERS)	JUNE 2018	SC4618	$7.50
WIDE-RANGE LC METER CLEAR CASE PIECES	JUNE 2018	SC4609	$7.50
TEMPERATURE SWITCH MK2	JUNE 2018	05105181	$7.50
LiFePO4 UPS CONTROL SHIELD	JUNE 2018	11106181	$5.00
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DSP CROSSOVER/EQUALISER DAC BOARD	MAY 2019	01106192	$7.50
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Tricky fix for DAB+/ FM/AM Radio

I am having problems getting the DAB+/FM/AM Radio (January-March 2019; siliconchip.com.au/Series/330) working.

I initially purchased the Micromite+ Explore 100 as a kit from your Online Shop. I assembled it and connected the recommended 5-inch touchscreen. To test it out, I modified Geoff's Graham's Super Clock (July 2016; siliconchip.com.au/Article/10004) to run on the Explore 100. It all worked well.

I then ordered the DAB+/FM/AM Radio Board, again from your shop, with all the components pre-mounted in the IC1 area and I also purchased the other surface-mount parts set. I then assembled this board, less the optional digital audio components.

I then assembled all the board into the 'stack' with just the front perspex panel. On powering up, one pair of the audio transistors kept overheating. Having read the letter and your reply to another reader in the March 2019 magazine, I removed the 2.2kΩ resistors from the ends of the diode and this stopped the problem. I will fix this properly after I've solved the following problems loading the firmware.

When I power up the radio, I get the following messages in the start-up log:

```
Changing to AM
setting radio mode to... 0
radio reset, loading firmware...
LOAD_INIT failed
HOST_LOAD error! 1st pass
HOST_LOAD error! 2nd pass
Bootloader load from flash: 1197
LOAD_INIT failed
loading AM radio firmware from
   flash...
done loading firmware from
   flash.
booting radio...
booted.
```

I tried re-loading the data into flash chip IC3 using the touchscreen controls. No errors were reported on the serial terminal, and it finished with the "Done" message. But it didn't fix the booting problem.

I then used a PICkit 3 to re-load the Explorer 100 with the full hex file from your website. No errors were reported, but the terminal program seemed to indicate the baud rate was wrong by printing strange characters. I could not resolve this, so I re-loaded MMBasic from Geoff's site. Then I loaded the radio firmware (crunched) from your website. I still got the above error messages.

I also checked the MISO, MOSI and SCK (SPI) tracks between the Si4689 and Explore 100 and its onboard PIC chip. I found no short or open circuits. I checked the voltage on the 3.3V rail, both 1.8V rails, and the 5V and -5V rails on the radio boards. They all measured as expected.

What do you recommend for the next step? (A. M., Eltham, Vic)

● Before we had time to formulate a response, we received a follow-up:

I used a CRO and multimeter to follow the steps during the start-up procedure. Downloading the Si4689 data sheet with flow diagrams, I could identify the steps in powering the chip up. It soon became obvious that the reset signal from pin 74 on the Explore 100 PIC was missing.

I checked this line and it was shorted to ground. I couldn't see any solder bridges or other problems on the PIC pins (100-pin QFP).

However, after lifting pin 74, the pin tested OK. The track appeared to be shorted to ground under the PIC chip. I could not find the short, so I cut the track adjacent to the PIC and linked pin 74 to the track. Success! It now boots and reports 'No Errors' on the screen.

We're glad you found and fixed this fault. This could be a flaw in the PCB. It's uncommon, but it can happen, especially when tracks are very close together, or close to copper pours.

We don't have as much experience with four-layer commercial boards as we do with double-sided boards; potentially, faults are more common on these. But many of the PCBs we purchase are also pre-screened for electrical faults, so it's surprising that a faulty board would end up with one of our customers.

DAB+/FM/AM Tuner not booting

I purchased the PCB for the DAB+/FM/AM Radio with the major parts pre-soldered to the PCB. I loaded the supplied HEX file into the micro using a PICkit 4.

All appears normal except no stations appear to be available, even though I am in a good signal area for all bands. I get the following errors on the serial monitor screen during booting:

```
Waiting for CTS Timeout
Load Init Failed
Patch Bootloader error (multiple
   times)
```

Can you please point me in the right direction to get it working. (P. J., South Australia)

● These errors point to a communication problem between the microcontroller and the radio IC. With no (or garbled) communication, no stations will be found. We had similar problems with our prototypes at times, which we eventually traced to bad connections in the large 40-pin header between the boards, as the pins were not making proper contact.

Apart from checking that, we suggest looking for problems on the boards between the microcontroller and the radio IC, eg, incorrectly installed or missing components, bad solder joints or solder bridges creating short circuits.

DAB+/FM/AM radio BASIC code not loading

I have been working on building the DAB+/FM/AM Radio and today got the Explore 100 board and display running.

I haven't finished the radio yet, but I attempted to upload the "DAB FM AM Radio Firmware CRUNCHED.bas" file into the Explore 100 board. It

reported that 64727 bytes were saved. I entered the RUN command and the terminal said:

[685] VAR RESTORE
Error: Variable name

The bottom of the LCD displayed:

Main Standby Config Dig Out

Nothing else was visible. Touching these areas produces a beep. Is this normal with the radio board not installed? (B. K., Iowa, USA)

● It sounds like the BASIC program has been corrupted during the upload process and contains an error. The actual "DAB FM AM Radio Firmware CRUNCHED.bas" file is 66104 bytes (not 64727). Try uploading it again, or alternatively try flashing it with the HEX file using a PIC programmer.

Larger flip-dot display wanted

I've just built one of four flip-dot displays that I intend to use for a clock, as described in your April 2019 issue (siliconchip.com.au/Article/11520). It's being driven by an ESP8266 module using internet time (NTP). I imagine others are doing this as it's a great application for flip-dot displays.

The display works well, switching reliably even when horizontal. However, it is a little hard to read. While I know that it would require more than twice the parts, is there a plan to describe a larger version; say 7x5 pixels? (D. S., East Melbourne, Vic)

● We're glad to hear that you're using our flip-dot display design. Although we did not go into much detail, the article notes that larger displays can be created by stacking multiple display modules, so we don't currently have plans to work on a larger version.

If you built 16 modules and connected them eight wide and two high, that would give you a four-character display with 6 x 10 pixels each.

Alternatively, since you are displaying time and therefore only need numbers, you could tweak the font to give maximum clarity in this role. A font similar to a 7-segment display might be more legible for a clock than the one we provided.

Can a DFPlayer Mini be added to DAB+ Radio?

I am thinking of building the DAB+/FM/AM Tuner (January-March 2019; siliconchip.com.au/Series/330) in the near future and have a couple of questions about the design.

Would it be possible to connect a DFPlayer Mini module, as described in the December 2018 issue (siliconchip.com.au/Article/11341) to the radio board via the CON8/CON9 expansion headers? All the required connections such as 5V, GND, TX and RX have been provided. Presumably, this could then feed audio into pins 4 and 11 of IC6 via pins 6 and 7 of CON8.

Would the existing line output networks on the DFPlayer module, as shown in Fig 2 of the aforementioned article, be appropriate with possible value changes? Obviously, a small subboard would be needed to match the pins of the module to CON8/CON9. (J. C., Creewah, NSW)

● What you are suggesting is along the lines of what we had in mind when we added CON8 & CON9 to the radio design. However, we haven't done any real design work for an add-on module yet. Your idea is workable.

The expansion header provides a way to feed audio into the analog multiplexer. As long as you can arrange for the signal level and DC biasing to be appropriate, any stereo analog signal source can be used.

You would need to add resistive dividers to reduce the audio levels from the DFPlayer module to those expected by the radio board; the radio chip itself produces around 70mV RMS, and you would want to match that to avoid huge jumps in volume when switch-

How to connect headphones to a bridge-mode amplifier

I have a couple of low-cost but excellent desktop audio amplifiers with inbuilt DACs (SMSL Q5 pro). I use these for video and audio editing on my PC.

These amplifiers, like most other similar units, have no provision for headphones and no line out sockets. This omission restricts their usefulness at night time and other odd hours.

Adding headphone outputs is difficult because these, like many newer amplifiers, actively drive the negative speaker terminals; they are no longer tied to ground like on older amps.

I cannot use a resistive divider to connect headphones to the outputs as the standard 6.5mm and 3.5mm stereo plugs all use a 3-wire scheme with a common ground for both channels.

I have scoured the internet for simple solutions without finding anything suitable. Can you suggest a practical passive or active solution to this? Would it be a good idea for a future project? (D. S., Nowra, NSW)

● It is possible to drive headphones from an amplifier operating in bridge mode, but you need to open up the headphones, separate the ground wires to the left and right sides and wire them to a four-core cable with a four-pin connector on the end (eg, mini-DIN).

We have done this before, and it works fine, but it's best if you modify headphones that can easily be opened up (ie, held together with screws rather than clips/glue). You can then make an adaptor cable so the headphones can still be used with a regular 3-pin socket, where the left and right grounds merge in the adaptor.

Without using transformers (which probably would negatively affect sound quality), the other option is to open up the amplifier and find a ground point on the PCB, then wire the headphone ground to this via a high-value electrolytic capacitor, with its positive terminal to headphones.

You can then connect the headphone left and right signals to one of the output terminals on each side.

How well this works depends on the amplifier design, but it should work in most cases.

Ultimately, we think it's easier and better to use a separate amplifier intended for use with headphones. For example, our High-performance Stereo Headphone Amplifier described in the September & October 2011 issues (siliconchip.com.au/Series/32). It sounds great, and it can even drive speakers, as long as you don't need a huge amount of power.

ing sources.

These signals should be DC-biased using the analog ground connection provided at pin 5 of CON8.

We included both SPI and UART interfaces on CON8 so that a wide range of different potential audio sources could be added to the radio.

The radio software would need to be modified to switch the multiplexer and send the appropriate control signals; the changes required are quite straightforward.

Can't get dimmer remote control to work

I built John Clarke's recent dimmer design (Versatile Trailing Edge Dimmer, February-March 2019; siliconchip.com.au/Series/332).

When using the touch plate, it works well. However, I cannot get the remote control to work. I have tried two remotes and replaced batteries in both and also checked my soldering around IRD1 many times!

The 47Ω resistor and 100µF electro feeding IRD1's pin 3 have both been checked for value and leakage and found to be OK. I would appreciate any help to resolve this. Thank you in advance. (N. H., Sanctuary Point, NSW)

● Please check that you are using the SF-COM14865 remote control and have the Murata IML0688 Fresnel lens over the infrared receiver. Is the cell inserted with the correct orientation in the remote control?

Also, make sure there are no solder bridges on the dimmer PCB that could cause the output of the IR receiver (pin 1) to be shorted out.

Alkaline vs carbon zinc cell leakage

On page 110 of the February 2019 issue, you wrote that "Alkaline cells are more prone to chemical leakage than the earlier carbon-zinc types".

I am now confused as to what battery type I should buy for emergency backup devices like radios and torches, that I keep in case of power failures at home and in my car. I seldom use these pieces of gear and could forget to check the batteries.

So should I buy carbon-zinc batteries for these applications? I only buy the best quality alkaline cells for everything, but for items that I use once in a blue moon, would carbon zinc be better to prevent battery leakage? (A. R., Newport, Vic)

● Alkaline cells have a very long shelf life due to low current leakage, so these are still the best choice for emergency backup. These cells typically only start to leak when completely discharged. It is wise to check the cells on occasion, both to ensure they still have capacity and to look for possible electrolyte leakage.

Carbon-zinc cells have a shorter shelf life due to a higher internal leakage current and have a lower capacity than alkaline cells. But they are acceptable for low-drain use as long as they are fresh. These cells can also leak electrolyte when discharged, either through self-discharge or power drain when in use.

On balance, alkaline cells are almost always the better choice.

Can battery desulfator be used while charging?

Silicon Chip is a great magazine. I look forward to my copy every month. I just finished building two of your MPPT Solar Charger and Lighting Controller units from the February & March 2016 issues (siliconchip.com.au/Series/296).

Can I use a battery desulfation unit like the Lead-acid Battery Zapper from July 2005 (siliconchip.com.au/Article/3118) or a Megapulse MkII unit in conjunction with the MPPT Charger without doing damage to the controller's circuitry? (K.W., Ballogie, Qld)

● You should not connect a battery desulfation unit to the battery while the MPPT Charger is connected, as it could damage the driving Mosfets in the MPPT Charger. Desulfation is a process that you only need now and then; it is better to disconnect the charger while doing that, then reconnected it after you have finished.

Accessing SD card from Raspberry Pi Tide Clock

I have built the Raspberry Pi Tide Chart (July 2018; siliconchip.com.au/Article/11142), and it is working satisfactorily. I want to activate the SD card reader on the LCD but am snookered whichever way I turn. There seem to be two ways to talk to an SD card, SPI or SDIO.

The LCD panel interface is using both hardware chip select lines for SPI(1) and the GP23, pin 16 needed for SDIO CMD/MOSI is used to drive the LCD reset line.

I have seen hardware and software for SPI(1) and for SDIO to communicate with a second SD card and hardware for it to communicate with SPI(2) but no high-level software to communicate with the SD card using SPI(2). I hope you can help. (J. N., Woorim, Qld)

● Your first challenge in using the LCD's SD card slot with the Raspberry Pi display breakout board used in the Tide Chart project is that it isn't actually wired up. See the circuit diagram on page 62 of the July 2018 issue. You will have to make the required connections between the LCD module and the Raspberry Pi somehow.

You could free up one of the hardware $\overline{CS}$ pins of SPI(1) by changing which pins are used to drive the LCD DC/RESET lines. Once you've re-routed the tracks, you just need to change our Python code to use the new pins.

We aren't sure exactly what you are trying to do, but if you just want to store some additional data, the easiest way to do that is to copy it onto the same micro SD card that contains the Raspberry Pi operating system. If you use a large enough card, the OS will only take up a tiny percentage and all the rest can be used for general purpose storage.

If you must have the data stored on a separate SD card, an easier solution might be to plug a USB card reader into the Raspberry Pi. They only cost a couple of dollars, are pretty fast, and the files will be readily available in a separate volume as soon as Linux detects that the card has been plugged in. Python code should have no trouble accessing the files either.

Attaching ultrasonic transducers to hull

I have built your Ultrasonic Anti-Fouling unit (May & June 2017; siliconchip.com.au/Series/312) and am finally getting around to installing it.

The instructions say to put silicone grease between the hull and transducer. Does this mean that we specifically have to use silicone grease or can we use any hydraulic fluid that doesn't leak out? (D.A.X., Netherlands)

● Anything that helps make a void-

free contact between the hull and transducer will do the job. We specified silicone grease because it won't dry out or otherwise go bad over time. Most other types of thermal grease should also be suitable.

Reluctor not triggering ignition system

I built your High-energy Ignition System for Cars (November-December 2012; siliconchip.com.au/Series/18) from a Jaycar kit, Cat KC5513. But I can't get it to work.

I intended to install the system on a Honda CB125S engine. I was restoring one and I had actually built/restored a second, more powerful version (stroked).

These engines originally came with points ignition, but later models had reluctor triggers with capacitor discharge ignition (CDI). All the parts were interchangeable, so I built the unit in the reluctor-triggered version and installed a reluctor trigger in my new engine.

I also converted the 6V system to 12V (by rewinding the stator and installing a modern voltage regulator). Amazingly, everything worked and this new engine started right up. But almost as amazingly, I could not get the engine to run above idle and spent hours trying to diagnose it.

I decided to simplify things and return to the original, stock engine which only had about 40 hours of operation on it. So I pulled the Kettering ignition out and installed the reluctor trigger that had been in the second engine. Now the ignition system will not deliver a spark.

I immediately tried the "diagnostic mode" (using LK2) in-situ and it fires the spark plug merrily at a fixed frequency. This suggests to me that the trigger input is suspect. I tried changing the trigger polarity using LK3 but that didn't help. I also installed a transistorised timing light to check for missing sparks, but no luck. It is not sparking at all.

I connected my digital Fluke multimeter set to AC volts to the reluctor trigger outputs and kicked the engine over. The meter shows a signal from the reluctor. It reads about 0.4V AC while the engine is spinning. It is a momentary transient event, so the peak voltage is likely higher. Can you help me get it working? (G. N., Minnesota, USA)

● Your reluctor output voltage does seem rather low. Typically, you should get about 30V AC at high RPM, reducing to around 2V AC at low RPM. This should be measurable with a multimeter, although at low RPM your measurement would be an averaged value, so possibly lower than expected. An oscilloscope is a better way to observe the waveform.

Also try measuring the reluctor resistance. Maybe it is open circuit. It should be around 1kΩ-10kΩ. Or it could have a shorted turn, preventing it from producing sufficient output, or the reluctor gap is too large. Check if this gap can be reduced. Also, check if the reluctor has one side connected to chassis.

If you have a mains transformer or AC plugpack which produces 5-12V AC, this voltage can be used to check if the Ignition System is working by using its output as a fake reluctor signal.

Check that the trigger voltage at TP TRIG (the collector of Q2) changes

Role of BAV21 diodes and fuse ratings in the SC200 amplifier

I previously wrote in to ask whether I could use a 1N4148 diode instead of a BAV21 for D2, the diode across the VAS transistors (Q7 & Q8) in the lower-power version of the SC200 amplifier module (January-March 2017; siliconchip.com.au/Series/308).

You pointed out the IN4148's reverse voltage rating was (just) insufficient, even with the ±42V DC rails from a 30-0-30V transformer. I decided to risk it anyway.

Could you explain what function D2 performs in the SC200 design?

After building the SC200 modules, I decided to build your Ultra low noise remote controlled stereo preamp (March & April 2019; siliconchip.com.au/Series/333).

Having just finished the preamp, I noticed that the right channel was intermittent at full volume. I also noticed that the output of the left channel SC200 module was low in volume and had distorted treble.

I feared that this might be due to my use of the 1N4148 diodes in place of the BAV21s. I thought I might have damaged the input section or VAS transistors.

But it turns out that I had only installed a 500mA fuse in the negative rail for the left channel, which unsurprisingly had blown (the other three fuses were the correct 5A values). Should I use 4A rated fuses instead, given that I am running the modules from a lower supply voltage?

The fault with the other channel turned out to be a faulty motorised pot in the preamp. The ground-side pin to the right channel track wasn't riveted properly on the phenolic board, and any pressure on the preamp PCB caused an open circuit-earth on the pot.

I used curved pliers to squeeze the rivet and stop the end of the pot track going open circuit. So far so good; it would be a pain to have to replace the motorised pot.

● D2 speeds up recovery from clipping, which improves amplifier stability when it's driven hard and also reduces distortion under those conditions. We explained this in more detail in the January 2013 issue (siliconchip.com.au/Article/1322). That article was on the Ultra-LD Mk.3 amplifier but it applies to the SC200 too.

The amplifier will work if you leave them out; many of our earlier designs lacked this diode, but it's better to have it in case you ever drive the amplifier module into clipping.

The DC fuse ratings are not that critical. You certainly could use 4A fuses with the lower supply voltages and they may provide slightly better protection. In reality, they are only likely to blow if the output transistors go short circuit and in that case, the instantaneous current will be well above 10A so they should blow pretty fast either way.

Thanks for explaining the interesting potentiometer fault. That is not one we've encountered before, but the phenolic boards used in many pots are quite fragile compared to fibreglass (FR4) boards.

from 5V down to 0V when an AC signal is applied to the reluctor input.

Once it's triggering, adjust VR3 for best results. See page 51 and 52 of the December 2012 issue for the adjustment procedure.

How to find parts at Digi-Key and Mouser

I live in the USA and want to build your June 2018 LC Meter (siliconchip.com.au/Article/11099). I purchased all available parts from your Online Shop but I'm having trouble finding the rest of the them at Digi-Key or Mouser. Your parts list doesn't give me sufficient performance parameters to figure out which ones to order. (B. F., Virginia, USA)

● It's quite a laborious job to create a list of catalog codes, although it isn't difficult. You just need to go to the relevant website, type in the basic part parameters such as "47k 1/4w 1% axial resistor", then sort by price. Check the parameters of the cheapest match to see if it's suitable. If not, use the filter options to narrow down the selection, and repeat until you have found a suitable part.

In the cases of resistors, capacitors and so on, once you've found one, it's often easier to look for parts with different values in the same series.

Here is a list we've compiled for this project, not including the parts you already purchased from us:

- The Arduino Uno is available from many sources
- 100µH bobbin-style inductor:
Digi-Key 811-2030-ND
Mouser 580-11R104C
- 5V coil DIL reed relays:
Digi-Key HE100-ND
Mouser 934-HE721A0500
- 2-pin female header sockets:
Digi-Key S7035-ND
Mouser 437-8018700210004101
- PCB-mounting right-angle banana sockets (black & red):
eBay 111437231973
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Digi-Key S7037-ND
Mouser 437-8018700410012101
- 2-pin header:
Digi-Key S1011EC-02-ND
Mouser 855-M20-9990246
- shorting block:
Digi-Key S9337-ND
Mouser 151-8010-E
- LM311 (DIP-8):
Digi-Key 296-1389-5-ND
Mouser 595-LM311P
- 10µF 6.3V tantalum capacitor:
Digi-Key 478-10753-2-ND
Mouser 581-TAP106M035HSB
- 100nF ceramic capacitor:
Digi-Key 478-7336-2-ND
Mouser 594-K104K15X7RF53H5
- 100kΩ: Digi-Key S100KCACT-ND
Mouser 603-MFR-25FTE52-100K
- 47kΩ: Digi-Key S47KCACT-ND
Mouser 603-MFR-25FTE52-47K
- 6.8kΩ: Digi-Key S6.8KCACT-ND
Mouser 603-MFR-25FTE52-6K8
- 4.7kΩ:Digi-Key S4.7KCACT-ND
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- 1.3kΩ: Digi-Key S1.3KCACT-ND
Mouser 603-MFR-25FTE52-1K3
- 130Ω: Digi-Key S130CACT-ND
Mouser 603-MFR-25FTE52-130R

Motor Speed Controller questions

I have just built your High-Current Speed Controller for 12V/24V Motors, as described in the June 1997 issue (siliconchip.com.au/Article/4868), from a Jaycar kit (Cat KC5225).

I could not control the speed of my motor over its full range. When the speed setting is at a minimum, the motor is still rotating at considerable speed. Is it possible to control a motor's speed from 0 RPM to maximum RPM using this circuit and if so what modifications do I have to make?

Also, I accidentally shorted out the motor wires, and now the circuit won't function at all. The transistors look fine; however, there was a burning smell when the wires touched, so I am guessing the Mosfets need to be replaced.

Would the other components be OK? I didn't have a fuse on the power supply (not sure this would have helped) so am I right in saying only the Mosfets would be damaged?

I am planning to use a large heatsink for the Mosfets but no heatsink for diode D2. I think it would only be switched on for a short period and would not get hot. But when I tested the circuit with a 775 motor under load, I noticed that D2 was getting

Protecting MPPT Solar Charger from motor voltage spikes

My question is regarding the MPPT Solar Charger & Lighting Controller from the February and March 2016 issues (siliconchip.com.au/Series/296). I am wondering if this charger would be suitable to be permanently wired to an engine starting battery. Would back-EMF spikes from the starter cause damage to the circuit?

I am looking after a museum display diesel engine which is only started occasionally but the engine has no charging capability of its own. It is a 24V system with twin starters and draws about 1100A peak at first contact!

I imagine there would likely be some severe spikes fed back. Since starting takes less than three seconds, there is little actual charging required. (I. M., Scoresby, Vic)

● There could be voltage spikes generated by the starter motors, but these should be at least partially absorbed by the battery.

The spikes are unlikely to cause damage to the MPPT Charger as there are three 1000µF capacitors across the charger output, followed by an inductor before reaching switching Mosfet Q1 and diodes D2. These are the components most likely to be damaged by voltage spikes.

To make sure the charger cannot be damaged, we suggest that you add a 24V DC coil relay with 10A contacts between the output of the charger and the battery, via the normally closed contacts.

Connect the coil to the circuitry that energises the starter motor, so that the battery is disconnected from the charger during cranking.

A further refinement would be to power the relay coil via a series connected diode (1N4004) and with a 1000µF 25V electrolytic capacitor directly across the coil (ensure the polarity is correct).

That way the relay will switch off a short time after cranking finishes, allowing any voltage spikes from the starters to die down before the relay contacts close to reconnect the charger to the battery.

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hotter than the Mosfets. Why is that?

I will be using the circuit to power two type 895 24V motors (360W each) on my bicycle, so I need to make sure I keep these components cooled appropriately.

I am planning to use three or four Mosfets. The multimeter testing I did on the Mosfet/diode cases suggest the Mosfets and diode D2 can't be installed on the same heatsink, so how can I best keep the circuit cool? (C. V., Ballarat, Vic)

● The speed pot varies the control voltage from 0 to 5V, but this voltage is also affected by the feedback resistors from the motor negative (M-) terminal. This feedback is what is causing the motor to run faster at the lowest speed setting. You can alter the feedback resistor to reduce the effect.

The 18kΩ resistor is located near REG1 on the PCB and can be increased in value. We suggest you try 47kΩ. Alternatively, if you don't need the feedback, omit this resistor entirely.

You are right that it's probably just the Mosfets which have been damaged. Check that the PCB tracks connecting to them are intact and not fused. Diode D2 can run hot; it depends on the motor speed setting as to whether the diode conducts significant freewheeling current.

Changing D2 to a schottky diode with a sufficiently high voltage and current rating should significantly reduce its dissipation, to less than half that of a standard high-current diode. You can attach both diode and Mosfet to the same heatsink as long as you use insulating washers and bushes. SC

Coming up in Silicon Chip

4DOF Motorised Chair for Simulators
Motorised chairs can be used to increase realism in racing and flight simulators, but they're expensive. This article shows you how to build your own from scratch, including a Micromite-based motor controller interface which connects to your PC via USB and is compatible with a wide range of software.

Fluid logic and microfluidics
While most digital and analog logic is electronic, similar systems have been built using fluid (liquid or gas) flows. You may be surprised to find out how many devices have been built and how advanced they can be. Dr David Maddison looks at the history and state-of-the-art in fluid logic, also known as fluidics.

Micromite LCD BackPack V3
This new Micromite BackPack is still cheap and easy to build, but now supports larger touchscreens, plus has onboard provision for a real-time clock, temperature, pressure and humidity sensors, an infrared receiver and even more useful functions!

Quantum Cellular Automata
It is becoming harder to design faster CMOS-based chips, but this new technology could offer the solution. While QCA chips have not yet been manufactured, they could potentially operate at very high speeds (into the terahertz) and with even higher density than the latest CMOS technology.

Rechargeable LED bicycle light
This device uses a switchmode converter to drive a string of LEDs from a rechargeable lithium-ion battery pack. It has multiple light modes and automatically reduces the LED current to prevent overheating.

Six-way Stereo Audio Input Selector
This can be built as a standalone unit, to switch between six different stereo audio sources with an infrared remote or via illuminated front panel pushbuttons. Or it can be integrated into our ultra-low-noise remote controlled preamp from the March and April issues, expanding the number of inputs from three to six.

Note: these features are planned or are in preparation and should appear within the next few issues of Silicon Chip.

The August 2019 issue is due on sale in newsagents by Thursday, July 25th. Expect postal delivery of subscription copies in Australia between July 24th and August 8th.

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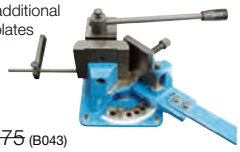

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(02) 9890 9111	(07) 3715 2200	(03) 9212 4422	(08) 9373 9999
1/2 Windsor Rd, Northmead	625 Boundary Rd, Coopers Plains	4 Abbotts Rd, Dandenong	11 Valentine St, Kewdale

07_SC_270619

Specifications & Prices are subject to change without notification. All prices include GST and valid until 31-07-19